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ASPECTS OF MECHANICAL BEHAVIOR OF ROCK UNDER STATIC AND CYCLIC LOADING. PART B. MECHANICAL BEHAVIOR OF ROCK UNDER CYCLIC LOADING

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MECHANICAL BEHAVIOR OF ROCK UNDER CYCLIC LOADING

Semi Annual Report

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by

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"Mechanical Behavior of Rock Under Cyclic Loading", Part B of "Aspects of Mechanical Behavior of Rock under Static and Cyclic Loading"

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The mechanical behavior of additional hard rock types under cyclic uniaxial compression and tension was studied, and a program of cyclic triaxial compression testing was initiated. All rocks (granite, sandstone, limestone, marble) exhibited cyclic fatigue characteristics in both tension and compression with fatigue strengths of 55-70% within 10^5 - 10^6 cycles. Prefailed granite exhibited substantial fatigue endurance. An inter-relationship between compression fatigue and the complete stress-strain curve has been demonstrated. For the same maximum stress cyclic stress amplitudes appear to affect fatigue life. In particular, indications are that compression-tension cyclic loading could be most damaging. The process of fabric deterioration due to fatigue is localized in cyclic tension unlike cyclic compression where it affects the entire body subjected to repetitive loading. As a practical application of the results obtained thus far, it is recommended that a value equal to 50% of the established static strength (compressive or tensile) be used in design of structures in intact hard rock as the effective strength that can withstand static, dynamic or cyclic stresses. The complete stress-strain curve could be used to determine maximum allowable permanent deformation prior to cyclic fatigue. The fatigue strength of failed rock should not be overlooked in designing underground structures.

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Security Classification

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Security Classification

ASPECTS OF MECHANICAL BEHAVIOR OF ROCK UNDER STATIC AND CYCLIC LOADING

PART B: MECHANICAL BEHAVIOR OF ROCK UNDER CYCLIC LOADING

SEMI-ANNUAL TECHNICAL PROGRESS REPORT
September 1972

by

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PREFACE

This report covers the accomplishments of the third six-month period in the research program entitled "Mechanical Behavior of Rock Under Cyclic Loading," B. C. Haimson - Principal Co-Investigator. The program is Part B of a project entitled, "Aspects of Mechanical Behavior of Rock Under Static and Cyclic Loading" Contract H0220041). The report on Part A of the project is published in a separate volume.

ACKNOWLEDGMENTS

The reported research was monitored by Dr. Syd S. Peng of the Twin Cities Mining Research Center, U. S. Bureau of Mines. His cooperation is gratefully acknowledged.

The graduate research assistants who performed most of the reported experimental work were V. Rajaram, T. Tharp and K. Kim.

LIST OF FIGURES

SUMMARY

The reported investigation is the continuation of an extensive study of the cyclic fatigue phenomenon in hard rock. This is the phenomenon of premature failure occurring in materials subjected to cyclic or repetitive loading. A thorough understanding of rock mechanical reaction to such loading could help in the design of safe rock structures and has the potential of improving rock breaking methods.

The main objectives of the project during the reported period were to study the mechanical behavior of additional hard rock types under cyclic uniaxial compression and tension, and initiate a program of cyclic triaxial compression testing.

S-N curves were obtained for Berea sandstone and Westerly granite in uniaxial compression, for Indiana limestone and Westerly granite in uniaxial tension, and for Westerly granite in triaxial compression (confining pressure of 1,000 psi). All rocks exhibited cyclic fatigue characteristics in both tension and compression with fatigue strengths of 55-70% within 10^5-10^6 cycles. All these results reinforce the assertion that hard rock is fatigue prone. Design of structures in rock should not ignore the effects of repetitive loading. The fatigue strengths of each rock as determined by the reported tests could be used as the effective strengths of intact rock. Since not every rock in the field can be extensively tested, it is recommended that a value of 50% of the appropriate static strength (compressive or tensile) be used as the effective strength that can withstand static, dynamic and cyclic loading.

Cyclic compression tests in previously failed granite like the previously tested prefailed Georgia and Tennessee marbles, exhibited substantial fatigue endurance, although the fatigue life at each stress level was much reduced when compared with unprefailed rock. These results could be extremely useful to the design of structures where rock might have previously been deformed to beyond the limit corresponding to its compressive strength. Pillars, ribs or other structural components although "failed" could resist cyclic loading to an extent determined by appropriate S-N curves.

Additional experimental evidence was collected in support of an inter-relationship between rock compression fatigue and the respective complete stress-strain curve. Particularly in granite, the amount of permanent deformation exhibited by the upper peak strain in stress-controlled tests, the shape of the S-N curve, the amount of peak stress relaxation and the type of fatigue failure in strain controlled tests, all allude to a Class II rock type and match the characteristics of the complete stress-strain curve. The practical application of these results could be substantial. Determining the complete stress-strain curve for a rock is much easier and less time

consuming than preparing an S-N curve. Monitoring the amount of accumulated permanent deformation at a particular stress level (whether in a laboratory specimen or an underground structure) and comparing it with the allowable magnitude from the complete stress-strain curve could establish the stability condition and estimate the amount of cyclic loading that the rock can still withstand. The shape of the complete stress-strain curve could indicate the ranges of maximum stress for which the rock is more susceptible to fatigue effects. These are the regions of minimum allowable permanent strain, usually caused by those portions of the descending stress-strain curve having positive slopes.

Experiments in uniaxial tension with different cyclic amplitudes for same upper peak stress showed that the cyclic stress range considerably affects fatigue life. In particular, the experiments implied that compression-tension cyclic loading could be the most damaging type.

Previous investigation of the compression fatigue mechanism showed that the process of cumulative damage was spread through the entire specimen. In uniaxial tension fatigue, however, fabric changes due to cyclic loading appear to be very localized, i. e., a few of the more crucial existing microcracks slowly enlarge until one gains on the others, propagates and splits the specimen. Other than the very close vicinity of the rupture plane no changes were observed in the internal structure of the rock. The implication here is that, unlike compression fatigue, impending tensile fatigue failure may give little warning in terms of deformation away from the critical flaw.

In conclusion, it is felt that the basic mechanical response of hard rock to cyclic loading has been established. Additional work, i.e., triaxial compression and tension-compression will complete the investigation of fatigue effect under the most common loading conditions encountered in the field. More microscopic, acoustic emission and photomacrographic studies are to be conducted to determine the internal fatigue mechanism. The reaction of non-intact rock to fatigue loading will be further studied.

INTRODUCTION

Rock formations as well as rock structures are continually subjected to both static and dynamic loads. Static loads result from such sources as tectonic forces and the weight of the overlying rock. Dynamic loads are continually propagated through natural vibrations of the earth crust, and intermittently applied by major earthquakes, rock blasting, drilling, traffic, etc. The mechanical behavior of rock under static loading has been thoroughly investigated. However, rock reaction to the cyclic, pulsating stresses resulting from dynamic loads has been generally neglected with the exception of a few rather limited studies. It is a known fact that cyclic loading often causes a material to fail prematurely at a stress level lower than its determined strength under monotonic conditions. This phenomenon is commonly termed "fatigue". Tunnel walls, excavation roofs and ribs, bridge abutments, dam and road foundations are only a few of the rock structures that can be weakened by repetitive loading. Better understanding of cyclic fatigue may assist the engineer in preparing a more rational design that will eliminate premature failures. On the other hand, knowledge of fatigue characteristics may help improve rock breaking methods, e.g., drilling and blasting. It is, therefore, imperative that the effect of pulsating stresses on rock is fundamentally studied with the ultimate goal of deriving practical applications.

Such a study is now underway at the University of Wisconsin, and the present report covers the third six-month period of a three year program to investigate the mechanical behavior of rock under cyclic loading. In the first year (1) a thorough literature survey was carried out and an extensive experimental investigation was initiated. White Tennessee marble and Indiana limestone were tested under cyclic uniaxial compression, Pink and White Tennessee marble were tested under cyclic tension.

The main results of the first year program were:

1. All tested rocks were weakened by cyclic loading whether under compression or tension, if the lower peak load was near zero, and the upper peak load was held at a level above a threshold, typical to the particular rock. The threshold appeared to be within the inelastic range of the stress-strain characteristics.

2. Failed marble exhibited substantial strength under cyclic compression.

3. In cyclic uniaxial compression both the axial and lateral strains underwent large permanent strains (cyclic creep). The average Young's modulus decreased during the test; the Poisson's ratio increased. The volumetric strain underwent cyclic compression dilatancy.

4. The amount of cyclic creep between the first cycle and failure appeared to be limited by the complete stress-strain curve.

5. Fabric analysis was conducted in cyclic compression specimens using stress-strain data, acoustic emission, optical diffraction techniques, and a photomicrographic study. The indication was that microcracking initiated from the very first cycle, and some cycles thereafter. A steady state period followed, characterized by a near stagnation in crack initiation. Thereafter a period of crack extension and coalescence, culminated in propagation and faulting. Within the above frame of fatigue mechanism, differences were observed between the non-porous marble and the high porosity (14%) limestone (1).

Based on the above results a number of practical applications were suggested. The qualification was made, however, that more experimental work was needed to (a) confirm the obtained results in other rock types, (b) to investigate other loading configurations and (c) simulate more realistic rock conditions.

The present report covers the work performed in the third semi-annual period of the project. Results are presented of cyclic fatigue studies of two additional rocks in uniaxial compression, two additional rocks in cyclic tension, and the initial testing under cyclic uniaxial compression. The conclusions of an investigation of the mechanism of fatigue in uniaxial tension are also discussed.

LABORATORY EQUIPMENT AND EXPERIMENTAL PROCEDURES

Rock Description

The rocks tested during the reported stage of the program were Indiana limestone, Pink Tennessee marble, Berea sandstone and Westerly granite. The first two rocks were described in the annual report. A brief description of the other two follows:

Berea sandstone is light gray in color, and consists of 99% quartz. It is finely grained, very porous (∿19%), and has visible bedding planes.

Westerly granite has very low porosity (∿1%) and fine grain size. It contains approximately equal amounts of quartz, microcline and plagioclase, and 5% biotite.

Specimen Preparation

All the specimens used in the present phase of the program were 1.0 in. in diameter, 2.5 in. long and were prepared as detailed in the annual report (1).

Apparatus

The two servo-controlled loading machines and the additional apparatus used in uniaxial cyclic compression and tension testing were previously described (1).

The triaxial compression cyclic tests were run in a specially constructed triaxial cell using the MTS machine. The triaxial cell was built after modifying a design described by Paterson (2). It has a bore of 2.0 in. and the capability of applying up to 15,000 psi confining pressures to 1.0 in. x 2.5 in. cylindrical specimens. Two 1.0 in. diameter pistons at either end of the cell are rigidly connected by a yoke. The lower piston transmits the load from the hydraulic ram to the specimen. The upper piston is forced by the yoke to move with the lower piston, thus allowing the confining oil to maintain its volume approximately constant The load from the specimen to the load cell is transmitted through the upper portion of the triaxial cell. Figure 1 is a detailed cross-section of the triaxial system. The variation of confining pressure with time has been monitored, and at 1,000 psi oil pressure it shows fluctuationsof ± 30 psi per cycle while maintaining the mean pressure constant at 1,000 psi. At the present no further improvements are planned, but it is believed that the ± 3% fluctuations have only a very limited effect on the results.

LEGEND:

1. Load Cell
2. Load Cell Adaptor
3. Pressure Block
4. Extender
5. DCDT Transducer
6. Yoke Bar
7. Mounting Block
8. Yoke Rod
9. Compression Nut
10. Upper Nut
11. Upper Piston
12. Upper Platen
13. Oil Outlet Port
14. Rock Specimen
15. Pressure Transducer
16. Piston Attaching Screw
17. Ram Adaptor

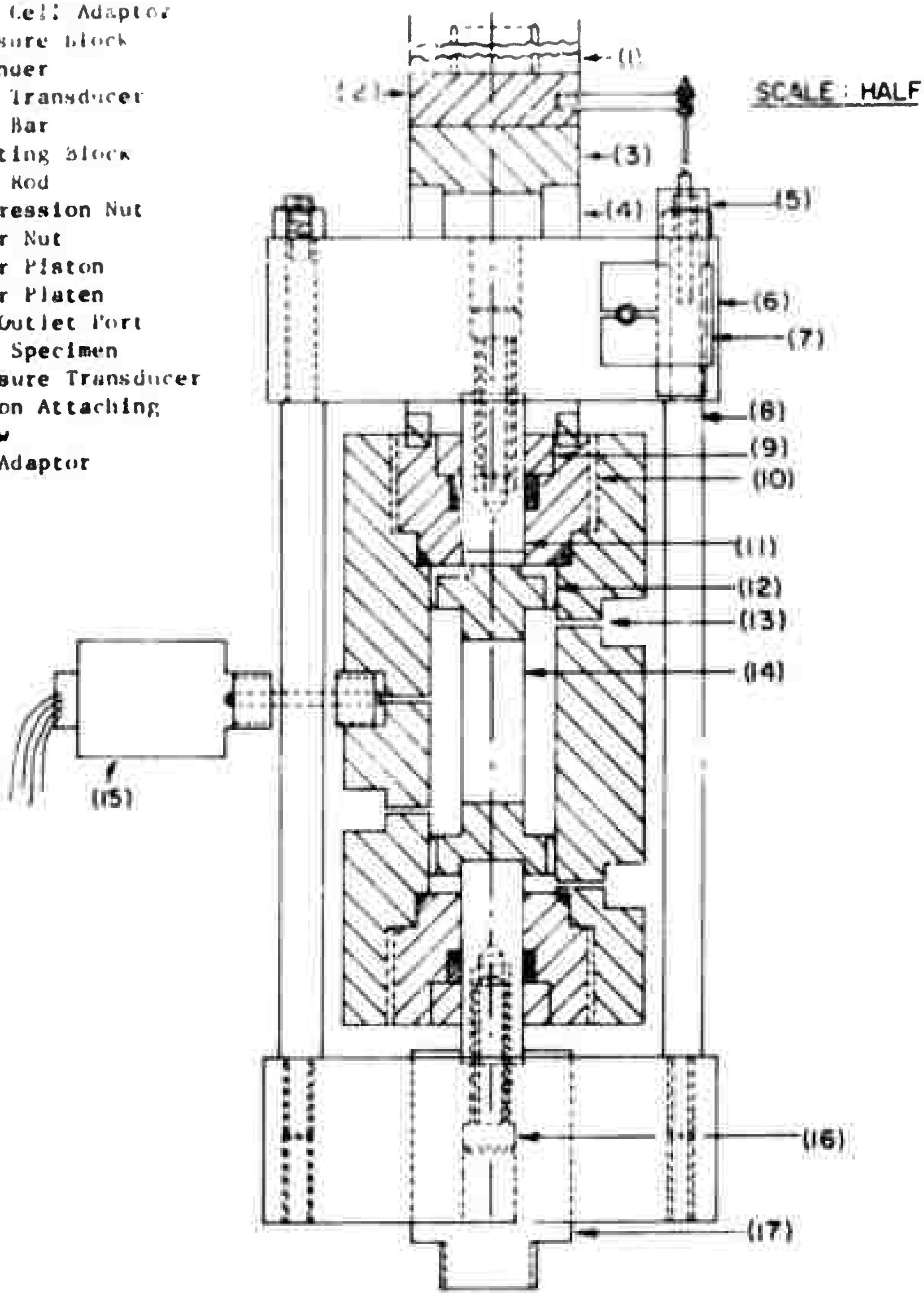

Figure 1. Front view of the triaxial cell for fatigue testing.

A pressure generating system has been built on a mobile 2' x 3' table, consisting of an "Enerpac" hand pump for filling the cell, a 0-15,000 psi positive displacement pump for accurate pressurization, a 6" Heise gage, an accumulator whose purpose is to prevent variations in confining pressure when the specimen deforms, and other valves and accessories (Fig. 2). A BLH 0-20,000 psi pressure transducer is directly connected to the triaxial cell and provides accurate continuous pressure monitoring. The longitudinal displacement of loaded specimens is measured indirectly by two DCDT transducers mounted on the outside of the triaxial cell.

Experimental Program

The objectives of the experimental program have been to (a) determine the mechanical behavior of rock under cyclic loading and provide data that is both basic and useful in engineering practice, and (b) study the internal mechanism that brings about cyclic fatigue.

Three major types of cyclic loading were used in the reported period, namely uniaxial compression, triaxial compression, uniaxial tension. The details of the testing procedure in uniaxial compression and tension can be found in reference 1. The only difference between the uniaxial and the triaxial compression testing procedures was that in the latter, specimens were subjected to a static confining pressure while cycling the vertical load. The triaxial cell was so built that the removal of a failed specimen and the insertion of a new one could be done without removing the cell from its rigid connection to the loading machine hydraulic ram. Specimens were jacketed with heat shrinkable tubing and installed in the triaxial cell which was then sealed and brought into contact with the load cell. The free annulus in the cell was filled with hydraulic oil and pressurized to the desired level while keeping the vertical load at a magnitude equal or greater than that of the oil. The vertical cyclic loading was applied as described in the annual report. Strain monitoring was indirectly done through two D.C.D.T. transducers mounted on the outside of the cell (Fig. 1). The acoustic emission was detected by attaching the piezoelectric transducer (1) to the outside surface of the triaxial cell.

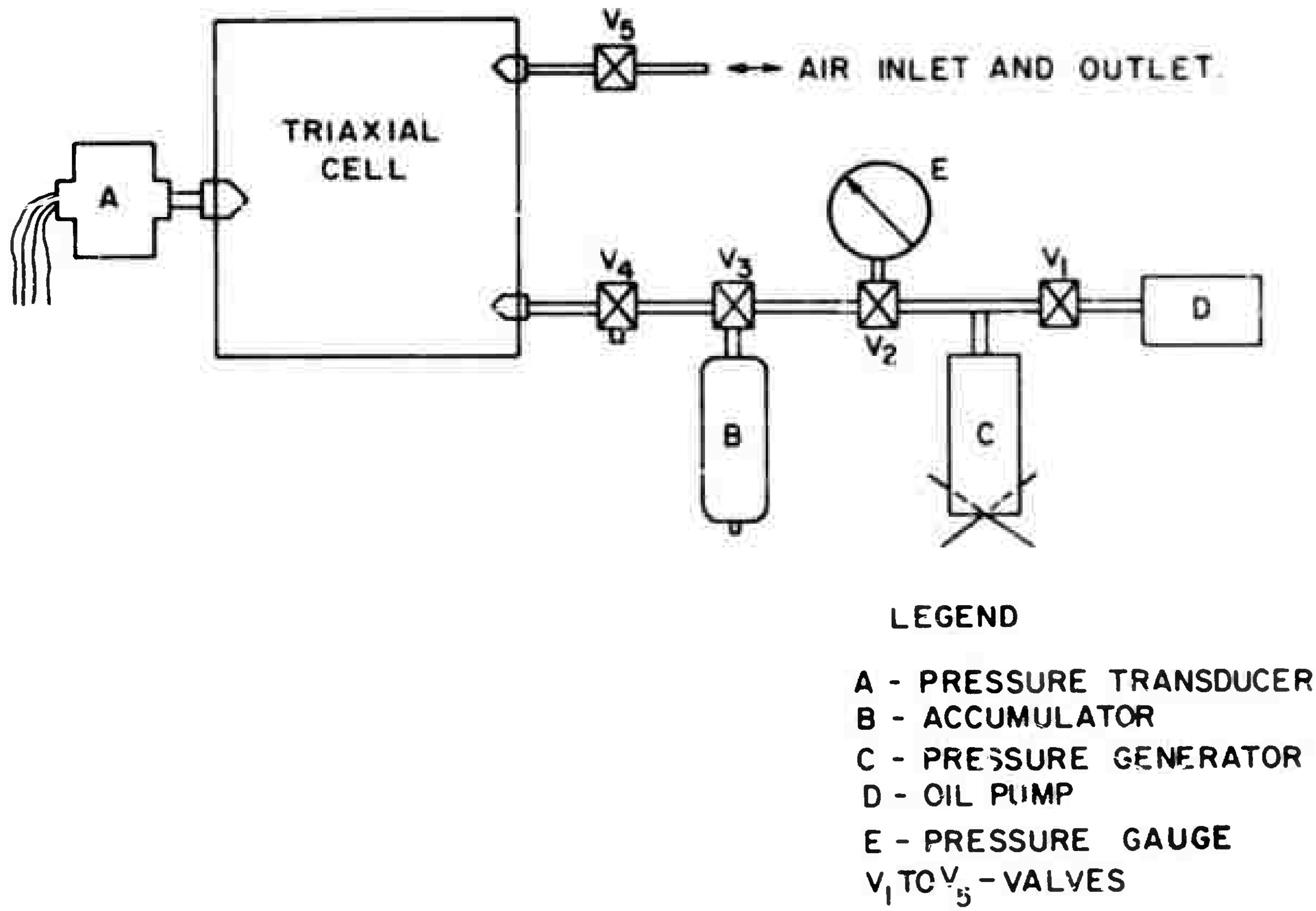

Figure 2. Schematic diagram of confining pressure generating system.

EXPERIMENTAL RESULTS

A - UNIAXIAL COMPRESSION

The two rocks tested under the present program, Berea sandstone and Westerly granite, were first loaded monotonically to determine their respective uniaxial compressive strengths at loading rates equivalent to "static" loading, 1 cps., 4 cps. In both rocks there was a substantial difference in strength between the "static" and the faster loadings ($\sim$20%), but no difference was observed between the two cyclic frequencies (Table 1).

Stress-Controlled Tests

In these tests the independent variable was the axial load. This load was programmed such that it followed a triangularly shaped cyclic function. The lower peak was kept constant throughout the program at about 200 psi, the upper peak was kept constant during a test but varied from test to test when desired. The values first used for upper peak loads were those close to the monotonic compressive strength for the rate comparable to the cyclic frequency used. Thereafter, the upper peak values were lowered in steps of 5% or less until no failure was obtained in more than 10^6 cycles. The results are detailed in the following sections.

(a) S-N Characteristics

In the first annual report (1) it was shown that both Tennessee marble and Indiana limestone exhibited cyclic loading fatigue when loaded in stress control. To confirm the results obtained two additional rock types were similarly tested under this year's program. Quantitative results in the form of S-N curves are given in Figs. 3 and 4. Both the sandstone and the granite exhibited fatigue behavior, i.e., they were weakened by repetitive loading. Within the limit set for these tests (10^6 cycles) the fatigue strength was as low as 55% in Berea sandstone and 60% in Westerly granite of the respective compressive strengths.

Although both rocks exhibited a definite weakening due to cyclic loading, their S-N relationship was quite different. In the sandstone a linear relationship seems to prevail (Fig. 3), while the best fitting curve for the granite could be divided into three linear portions exhibiting a sharp drop in strength with cycling in the upper 25%, followed by a drastic strengthening and increased resistance to fatigue in the next 5% and then again a rather sharp drop in the remaining 10% (Fig. 4). A tempting speculation regarding the granite S-N curve is that it may be related to the complete stress-strain curve for the rock (3). In the post-failure zone

TABLE 1

COMPRESSIVE STRENGTHS AT DIFFERENT LOADING RATES

Rock	Specimens Tested	Loading Rate (psi/sec)	Equivalent Cyclic Frequency (psi)	Mean Comp. Strength (psi)	Standard Deviation psi	Standard Deviation %
Berea Sandstone	10	100	"static"	10,400	380	3.65
	8	25,760	1	12,800	200	1.59
	6	103,040	4	12,800	166	1.30
Westerly Granite	3	200	"static"	38,200	250	0.83
	4	93,000	1	46,500	500	1.37
	4	372,000	4	46,500	250	0.68

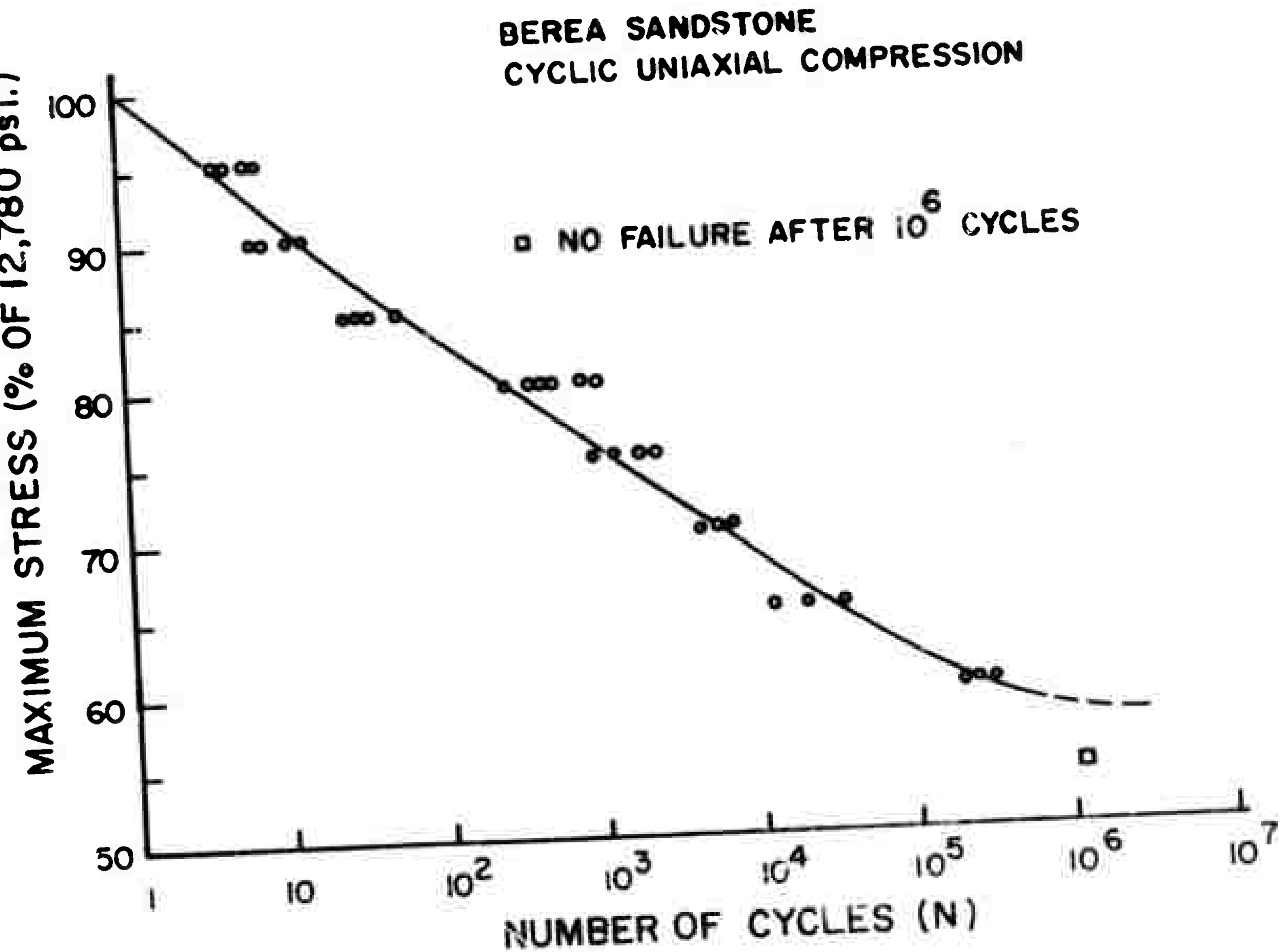

Figure 3. S-N characteristics in uniaxial compression--Berea Sandstone.

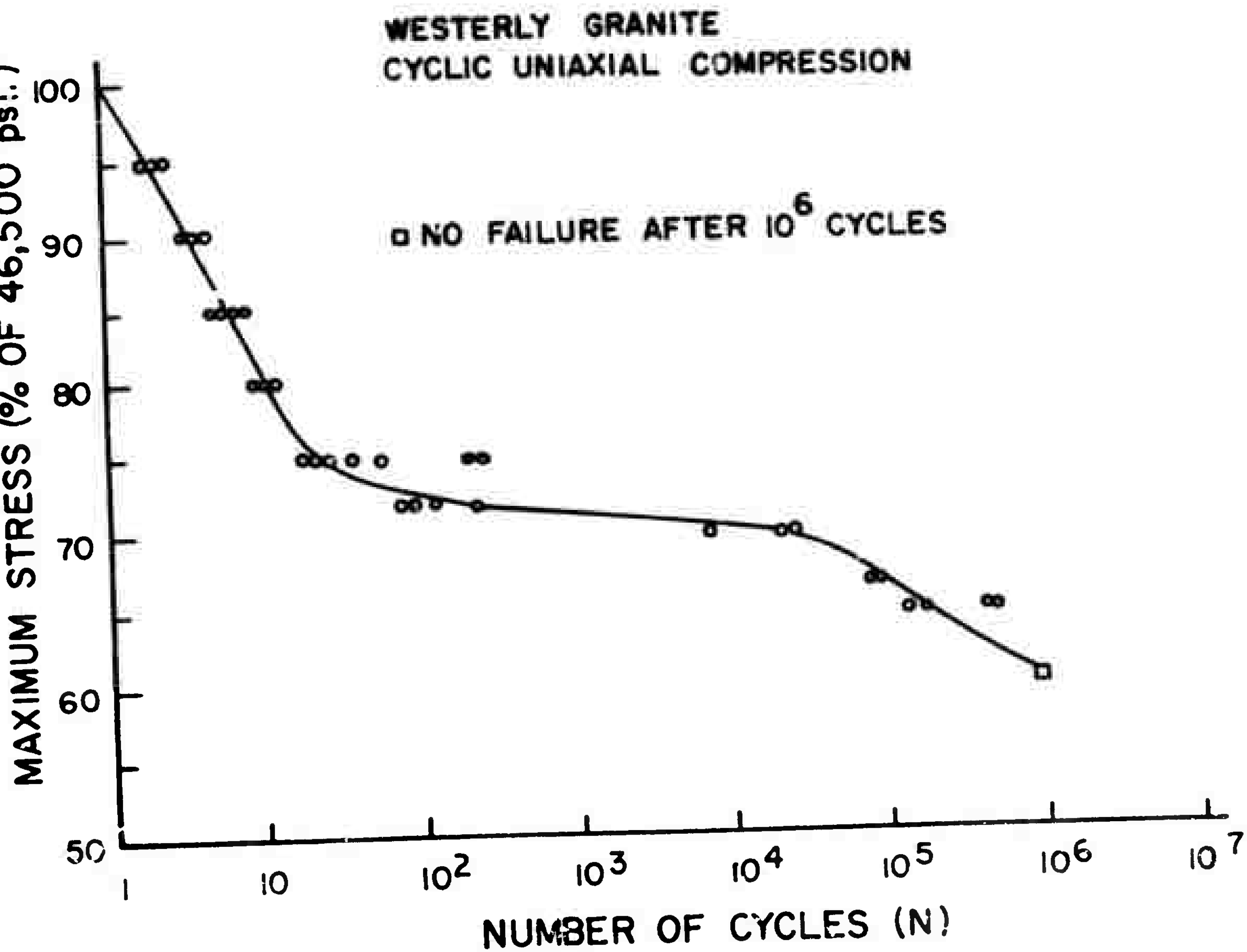

Figure 4. S-N characteristics in uniaxial compression--Westerly Granite.

this curve is unstable and has a positive slope in its upper quarter, followed by a negative slope for a small portion of stress and continued again by a positive slope (Fig. 5). The extent of the top portion of the descending complete stress-strain curve may coincide with the top range of the S-N curve (for which less than 100 cycles are sufficient to bring about failure). Similarly, the next two portions of the complete stress-strain curve appear to coincide with the continuation of the S-N curve. The implication suggested is that the extent of permanent strain exhibited by the complete stress-strain curve controls the fatigue life at different levels of maximum stress. Further observed phenomena which could be related to the complete stress-strain curve will be discussed in the following sections.

A practical application derived from the S-N results obtained thus far is that in designing hard intact rock structures, the fatigue strength at 10^6 cycles conservatively taken as one half of the measured static compressive strength (Table 2), would provide protection not only against static and dynamic compressive loads but also against cyclic stresses such as encountered in earthquakes, blasting, etc.

(b) Cyclic Stress-Strain Behavior

The basic cyclic stress-strain behavior was not different from that observed in previously tested rocks (1). Three stages (primary, steady state, tertiary) could always be identified in tests longer than 10 cycles. The first cycle invariably yielded the largest hysteresis due probably to permanent closing of existing openings and cracks and initiation of microfractures. As a result of the reduced porosity, the hysteresis in the granite was, however, very low as compared to the sandstone. Typical stress-strain curves are shown in Figs. 6 and 7.

The amount of strain difference between the upper peaks of the last and first cycles, the cyclic creep, was measured and the average values were plotted in Figs. 8 and 9. Comparing the granite results with the complete stress-strain curves of a similar rock type as obtained by Wawersik and Brace (3), it is noticed that similar to the two previously tested rocks (1), the cyclic creep at different levels of <u>S</u> is bounded by the ascending and descending portions of the stress-strain curve. In particular, the Class II character of Westerly granite is apparent in Fig. 8.

(c) Other Measurements

Additional measurements related to stress controlled compression cyclic tests are now at different stages of completion and will be presented in the forthcoming annual report. These will include data on lateral strain, volumetric strain, acoustic emission and microscopic examination.

<u>Stress Controlled Tests with Variable Upper Peaks</u>

An attempt was made to study the loading path dependence in stress controlled tests. While keeping the lower peak constant, the upper peak

TABLE 2

COMPRESSIVE AND FATIGUE STRENGTHS OF FOUR TESTED ROCKS

Rock Type	Static Compressive Strength (psi)	Fatigue Strength (10^6 Cycles) (psi)	$\frac{\text{Fatigue Strength}}{\text{Static Compressive Strength}}$ (%)
White Tennessee Marble*	21,150	17,500	83
Indiana Limestone*	9,500	6,470	68
Berea Sandstone	10,400	7,070	68
Westerly Granite	38,200	27,850	73

*see Reference 1.

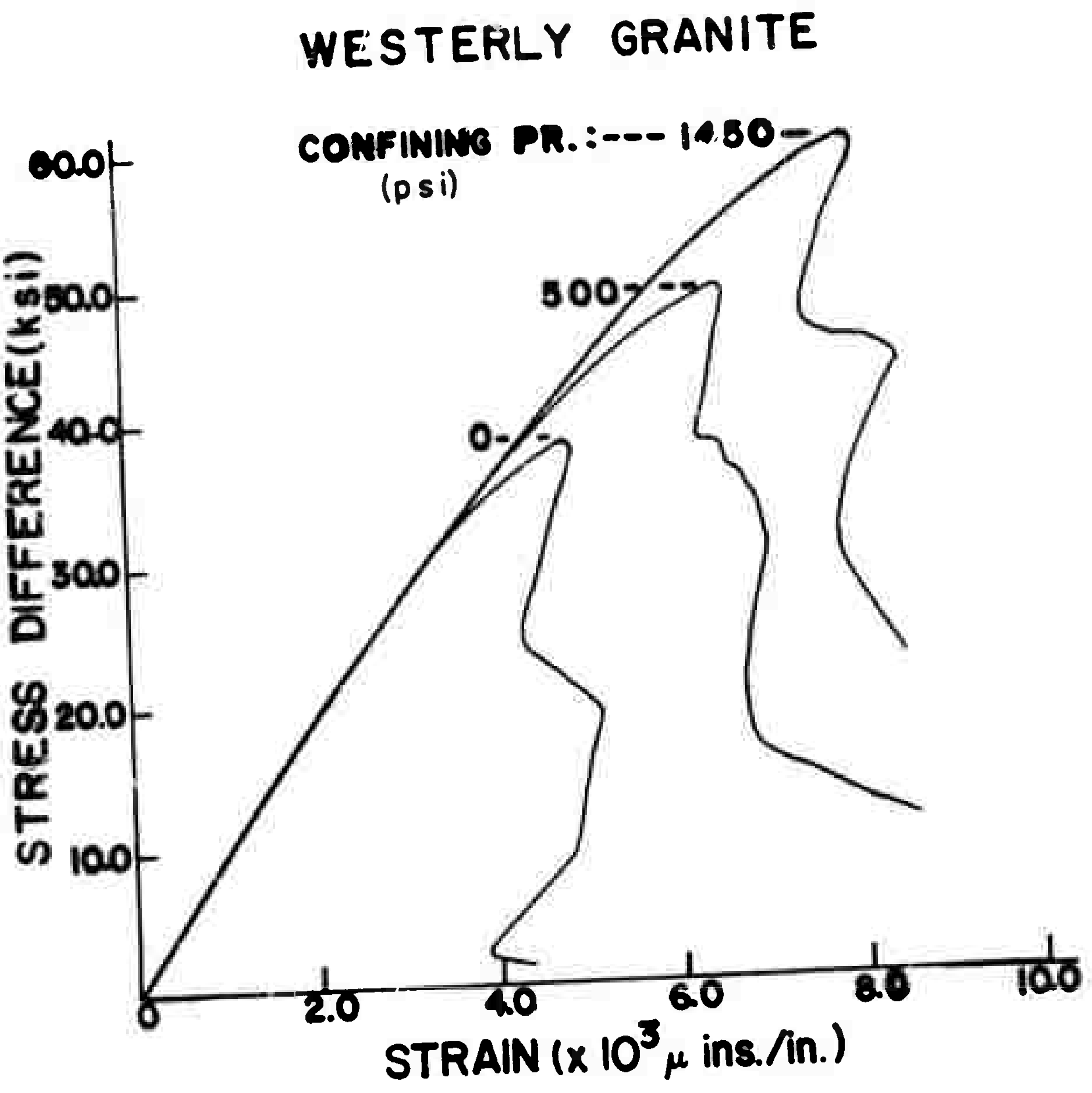

Figure 5. Complete stress-strain curves for Westerly Granite (after Wawersik and Brace).

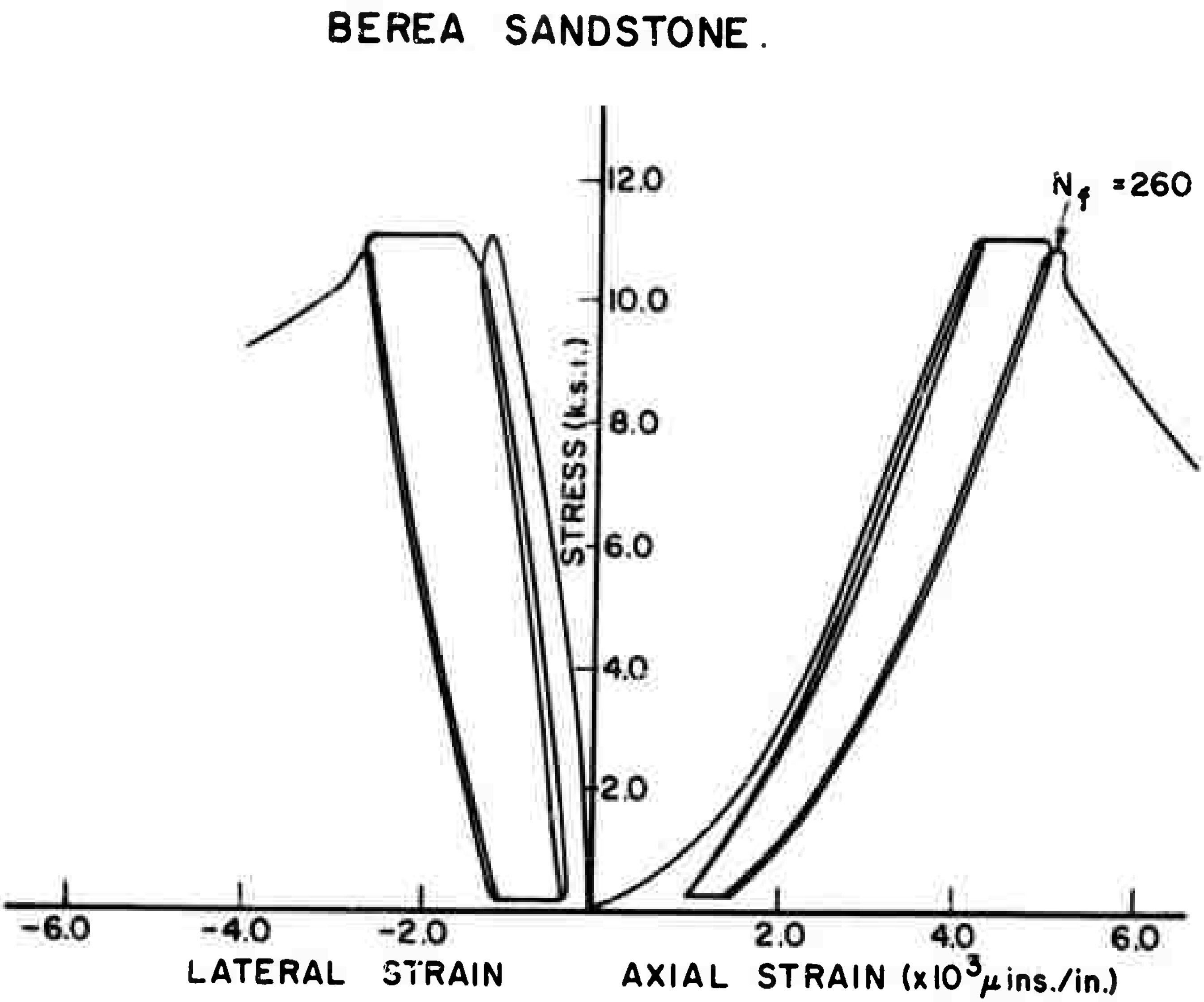

Figure 6. Typical stress vs. lateral and axial strain curves in stress controlled cyclic uniaxial compression--Berea Sandstone.

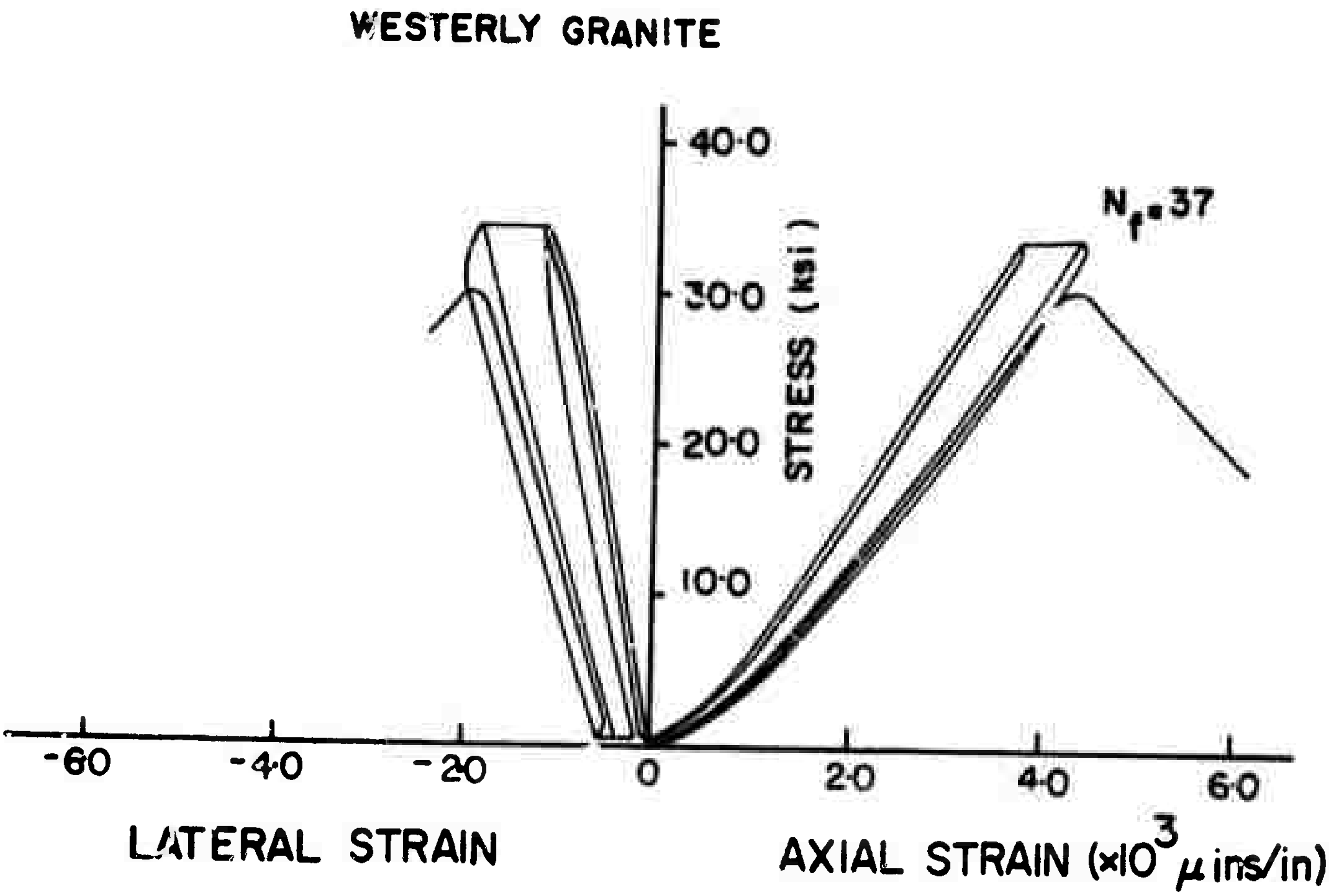

Figure 7. Typical stress vs. lateral and axial strain curves in stress controlled cyclic uniaxial compression—Westerly Granite.

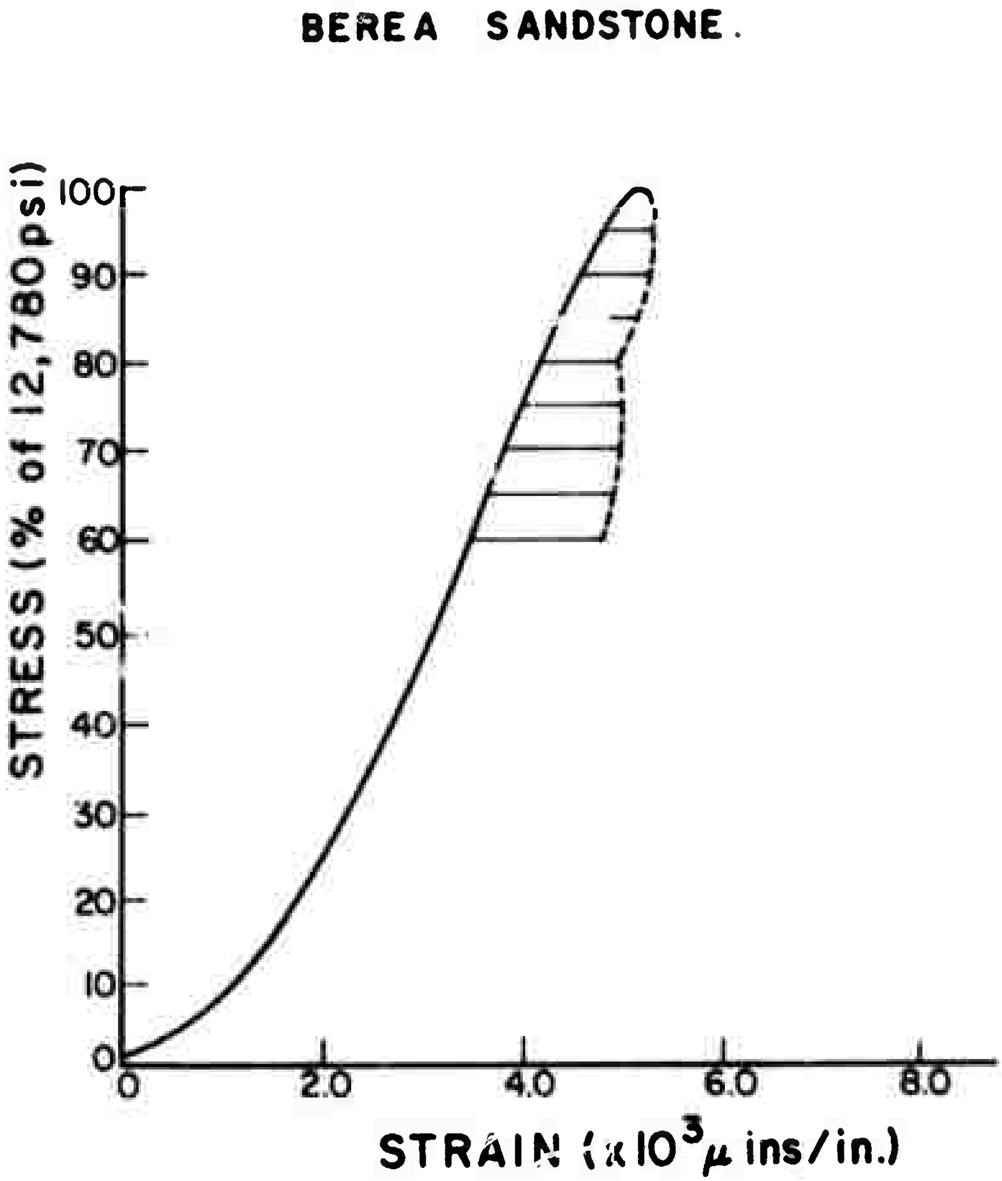

Figure 8. Upper peak strain cyclic creep (permanent strain) for various stress levels--Berea Sandstone.

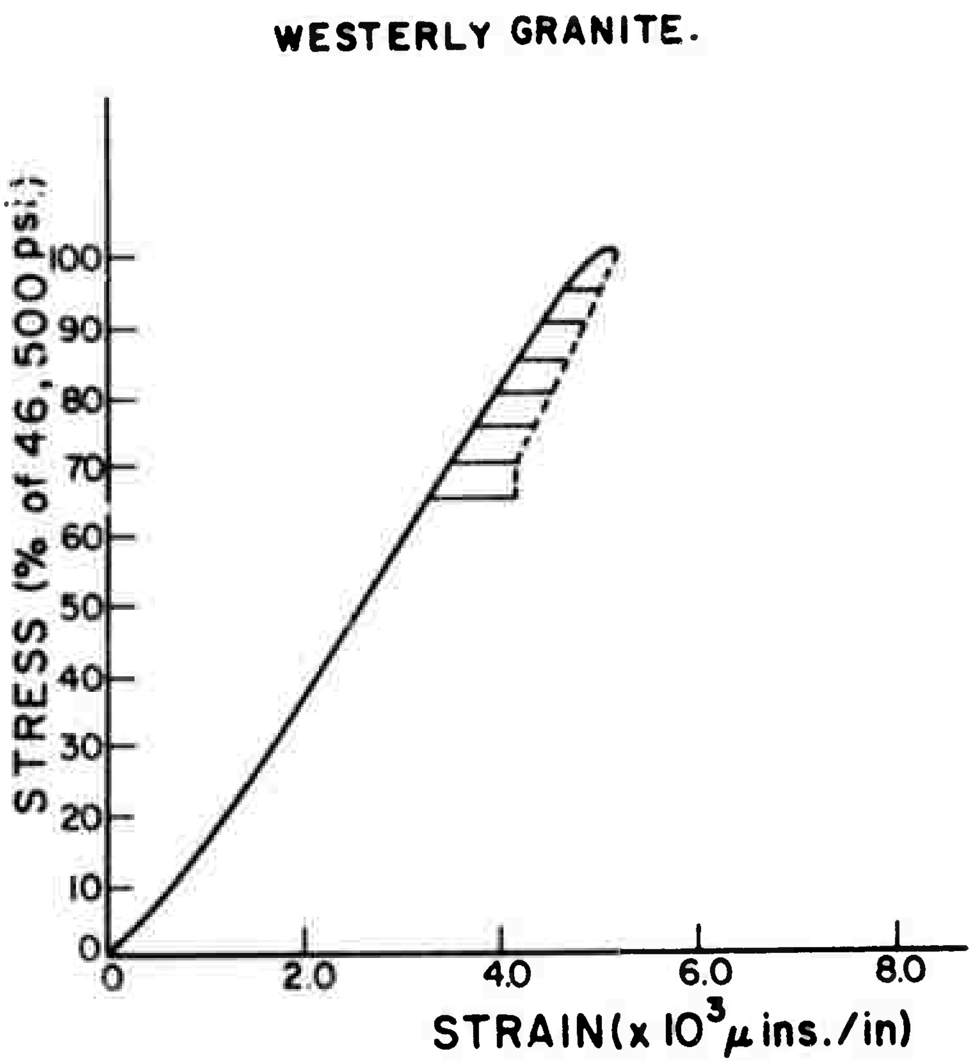

Figure 9. Upper peak strain cyclic creep for various stress levels - Westerly Granite.

stress was varied during the test and the number of cycles, as well as the total cyclic creep, were monitored. As shown in Figs. 10 and 11 the total amount of permanent strain at the upper peak level at which a specimen failed was consistently unaffected by the previous magnitudes of the upper peak. Whether the upper peak load was stepped up or stepped down, the total cyclic creep remained path independent. The consistency of this result was rather surprising. It is a further indication that the amount of upper peak level permanent strain actually controls fatigue failure. As has been stated above, it appears that the complete stress-strain curve provides the range for the maximum allowable deformation. This range is not path dependent as long as the path is within the complete stress-strain curve.

Stepping up or down the upper peak load during a test drastically affects the number of cycles to failure. Typical examples are shown in Figs. 10 and 11. Considerably more tests are needed to quantitatively determine the path dependency of fatigue life.

Stress-Controlled Tests of Failed Granite

The discovery of the complete stress-strain curve in recent years has changed the meaning of rock strength. The classical approach had been that rock subjected to loads equal or larger than its compressive strength would collapse violently and its load carrying ability eliminated. It has been demonstrated, however, (4) that under some conditions (like stiff machine loading, or strain-controlled loading) rock is capable of supporting substantial stresses even after it has reached its compressive strength. Such "failed" but active rock can be encountered in underground excavations, in pillars, sidewalls, etc. It was thus decided to test the ability of failed rock to support cyclic loading.

Two failed marbles were tested last year and the results were reported elsewhere (1). In the present program specimens of Westerly granite were loaded in strain-control to their compressive strength value, unloaded, and then cyclicly loaded in stress-control keeping the lower peak stress constant throughout the testing program. The limited amount of tests run so far is not sufficient to establish the S-N characteristic of failed granite. The indications are clear, however, that while the fatigue life is drastically reduced, the failed rock is still capable of supporting a considerable amount of loading cycles. Table 3 gives some typical differences in fatigue life between intact and failed specimens.

Additional work on fatigue of failed rock is planned in both sandstone and granite.

Strain-Controlled Tests

An extensive series of tests was run in both rocks under strain control (at 1 cps). The lower peak strain was kept constant at 480 μin/in throughout the program and the upper peak strain was varied from test to test. The value of the lower peak was chosen so that although it was relatively small

TABLE 3

TYPICAL FATIGUE LIFE
FOR INTACT AND FAILED WESTERLY GRANITE

Upper Peak Cyclic Load (% of Comp. Strength)	Fatigue Life of Intact Rock (cycles)	Fatigue Life of Failed Rock (cycles)
80	10	3
75	35	22
70	10,000	375
65	200,000	4,700

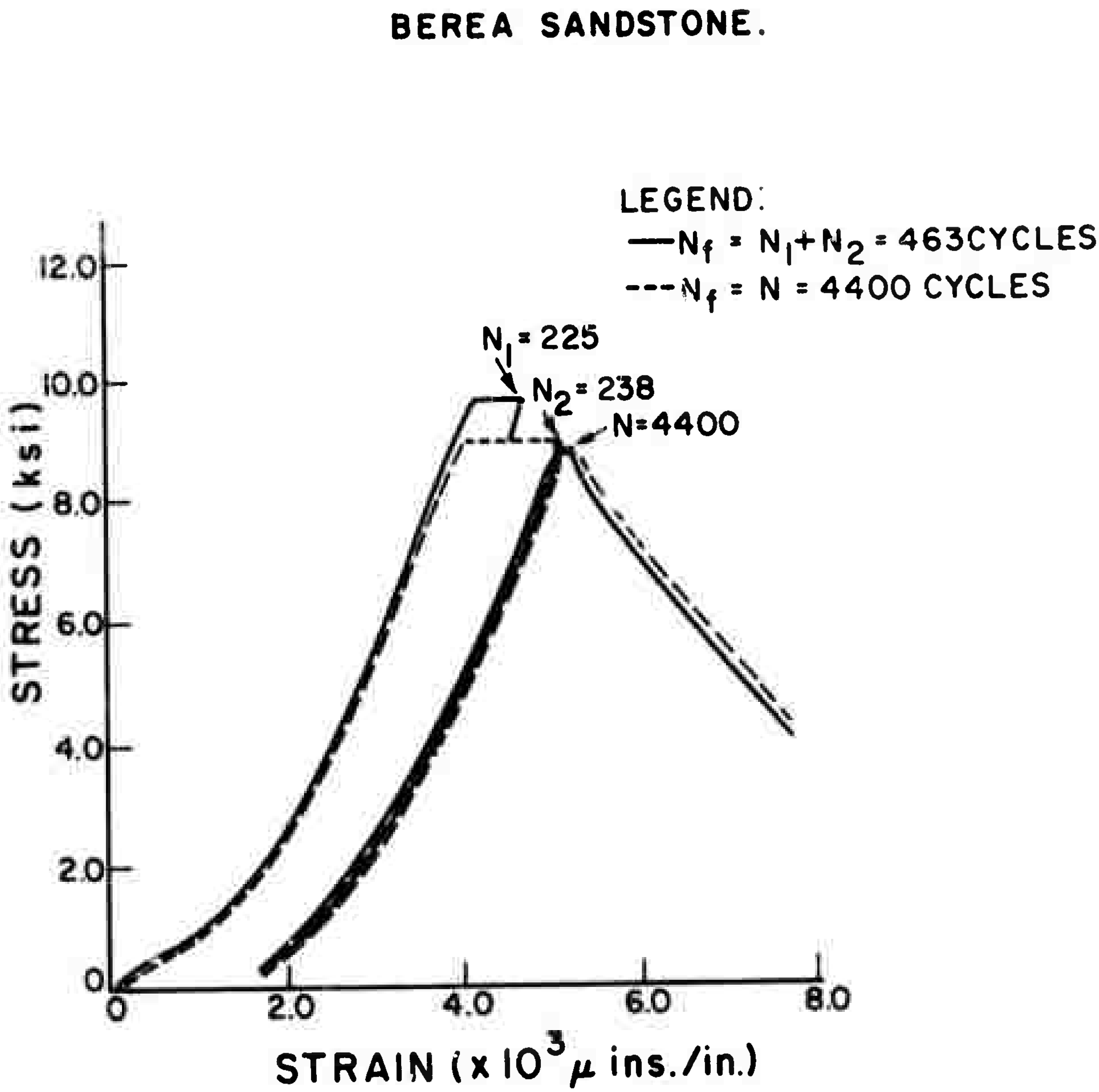

Figure 10. Path dependence in stress controlled cyclic compression tests--Berea Sandstone.

WESTERLY GRANITE.

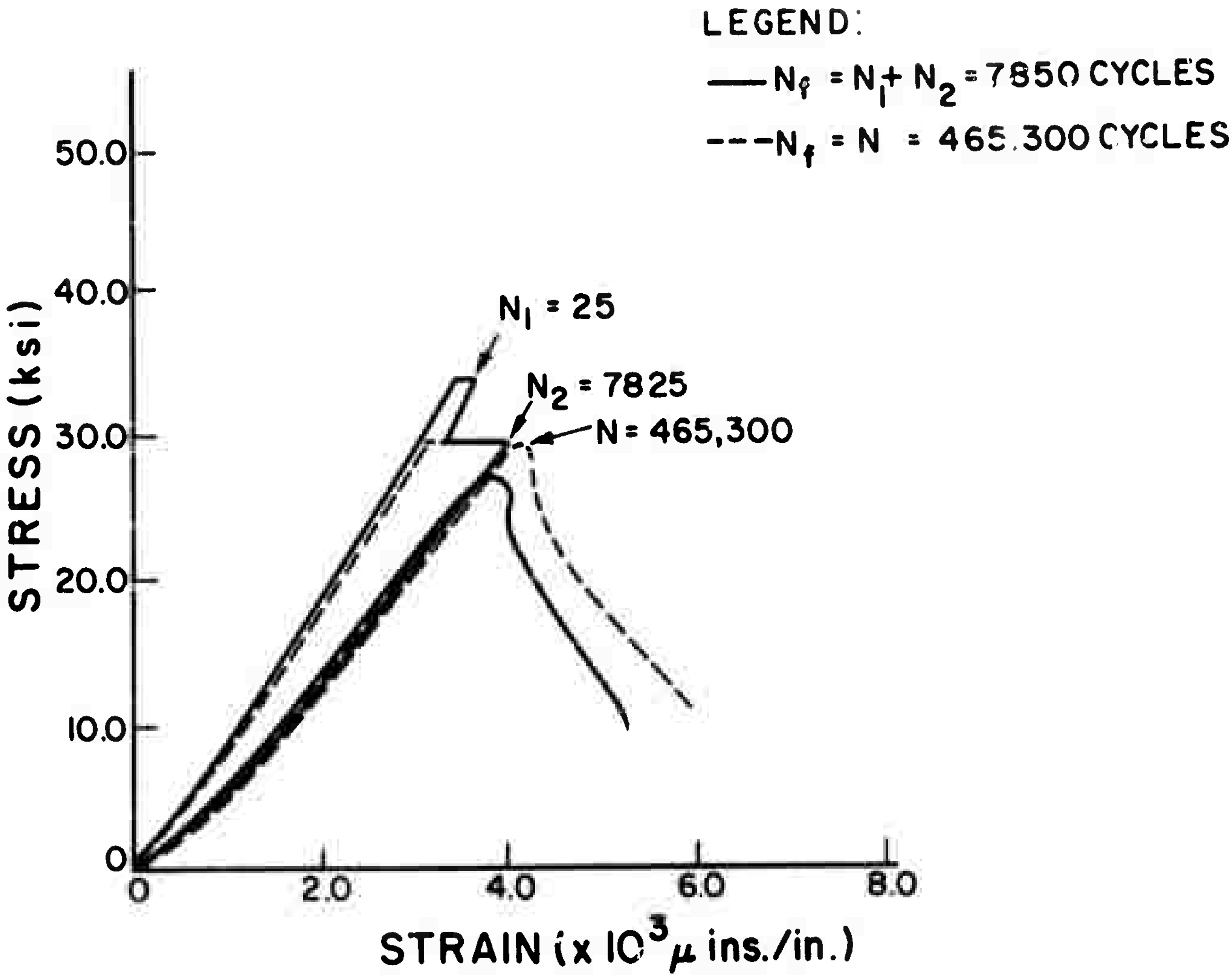

Figure 11. Path dependence in stress controlled cyclic compression tests--Westerly Granite.

it allowed the lower peak stress to relax during cycling without reaching zero stress, in which case the specimen would have lost contact with the loading platens. As in the stress-controlled tests, the number of cycles necessary to fatigue the rocks increased with the lowering of the upper peak strain. Fatigue life versus maximum applied cyclic strain was plotted for both rocks (Figs. 12 and 13) in the form of E-N curves.

The type of strain-controlled fatigue failure was significantly different from that encountered in stress controlled tests. In Berea sandstone failure was always slow characterized by crumbling at the outside surface through a process similar to spalling. Continuous crumbling rapidly reduced the amount of peak stress and accelerated the cyclic stress relaxation (Fig. 14a). In some cases the specimens eventually failed, or were considered failed when the amount of crumbling became excessive; in others they reached a kind of equilibrium that appeared to require for fatigue failure many more cycles than the 10^5 limit (Fig. 15). In Westerly granite the type of failure depended on the range of upper peak strain. In the 90-100% range fatigue failure occurred violently within a few cycles (Fig. 13) and with limited cyclic stress relaxation (Figs. 14b and 16). In the 75-90% range failure was considerably slower, and was considered complete when chipping occurred at the surface. The relaxation was dominated by a steady-state stage (Fig. 14c), and later the amount of stress drop increased (Fig. 16). At 70% and lower the fatigue process seemed to cease and no failure was obtained within more than 10^5 cycles, although considerable relaxation was observed.

The type of failure and the amount of stress relaxation to failure could both be related to the complete stress-strain curve. Using the curve for Westerly granite (Fig. 5) one can easily establish that in a strain controlled cyclic test, with the upper peak in the top 10-15% of the ascending curve, a relatively small amount of stress relaxation will cause the cyclic stress-strain curve to intersect the descending positively sloped section of the complete stress-strain curve. Additional cycling will carry the relaxation to the outside of the curve thus causing a violent failure. When the process of fatigue failure is slow and seemingly endless, in both granite and sandstone, it is probably due to the need for the upper peak stress to reach the zero value before complete collapse. This is the case when the cyclic stress-strain curve does not intersect the descending part of the complete stress-strain curve.

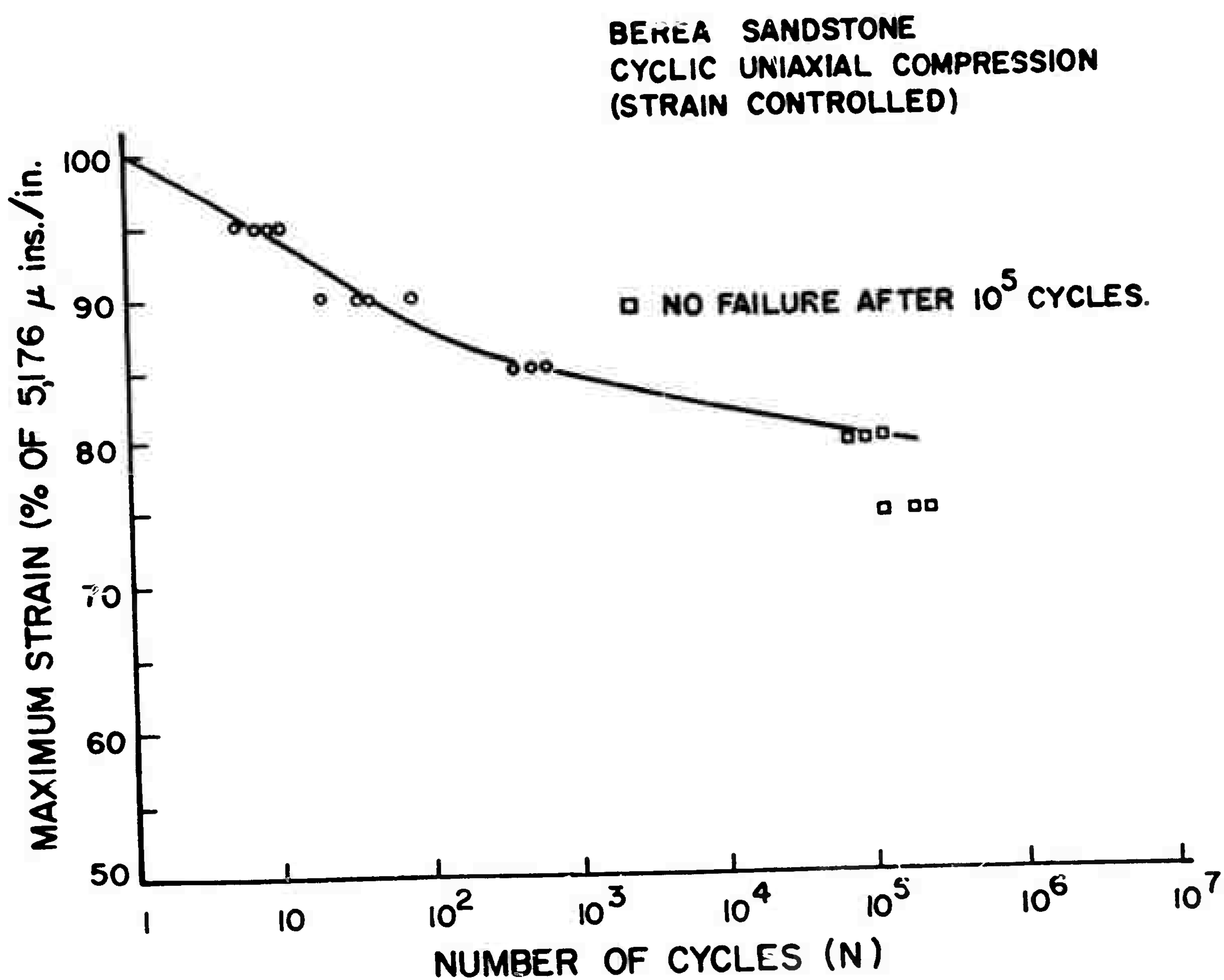

Figure 12. E-N characteristics in uniaxial compression--Berea Sandstone.

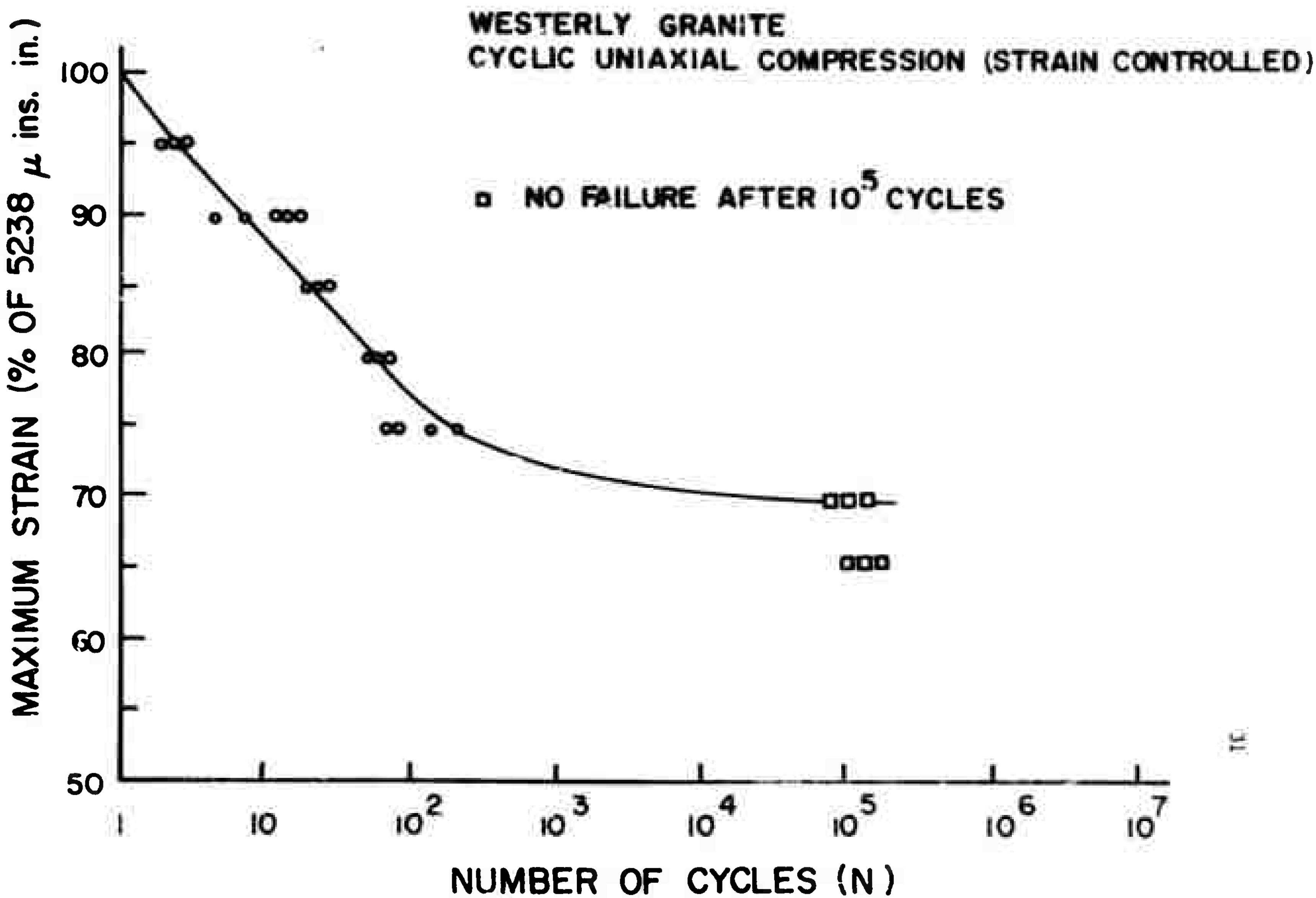

Figure 13. E-N characteristics in uniaxial compression--Westerly Granite.

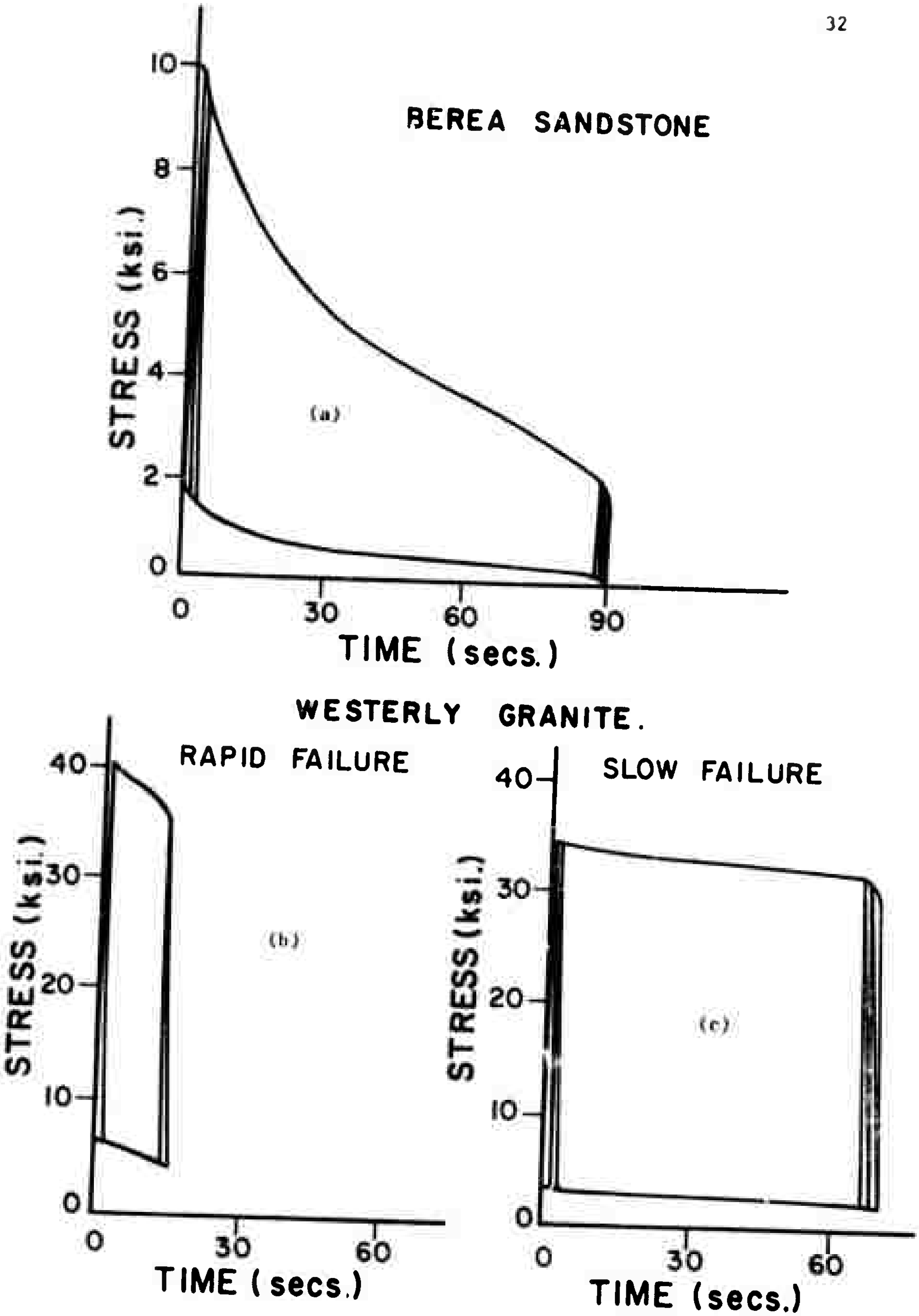

Figure 14. Typical stress cyclic relaxation curves.

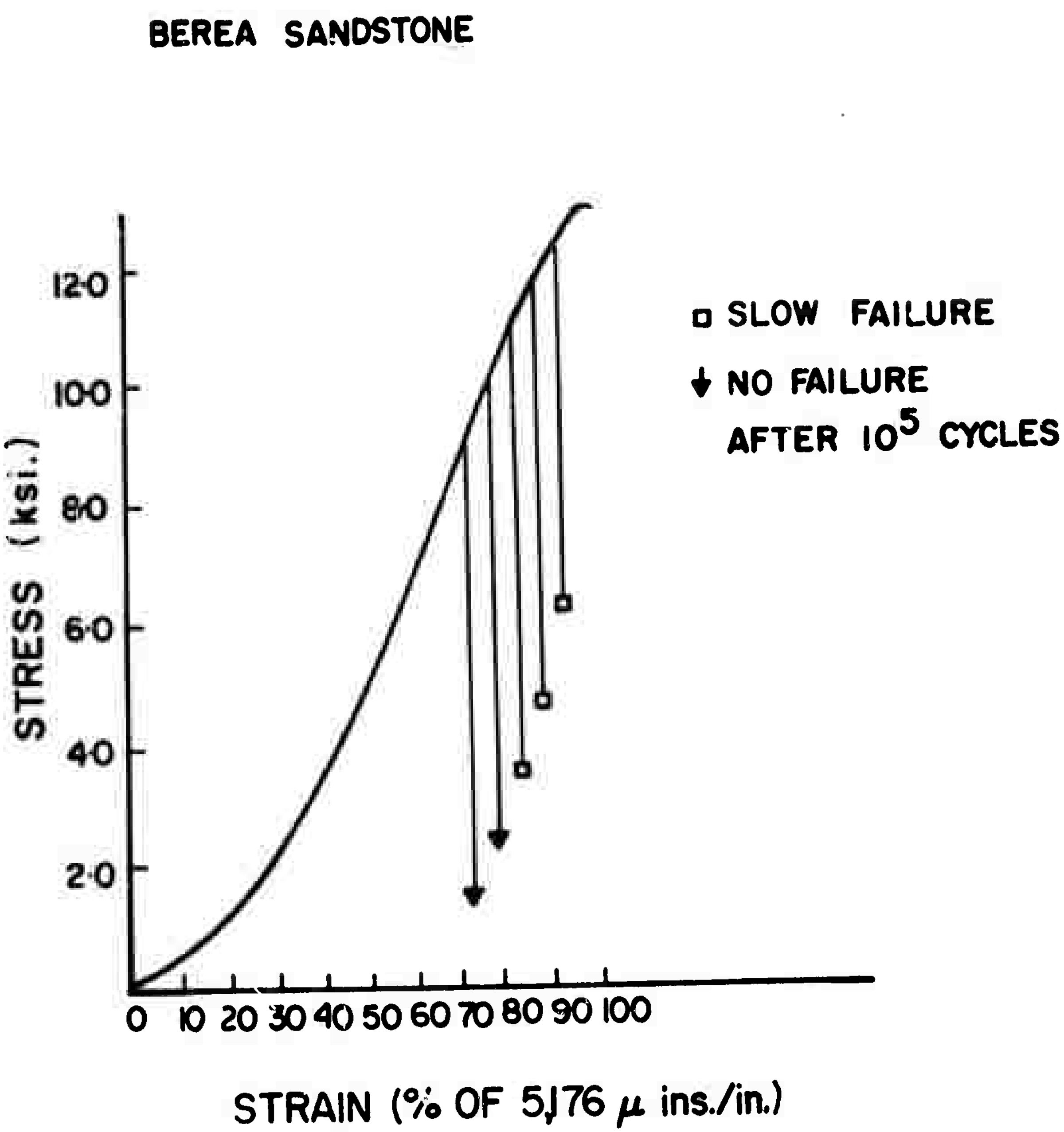

Figure 15. Upper peak stress drop at various strain levels--Berea Sandstone.

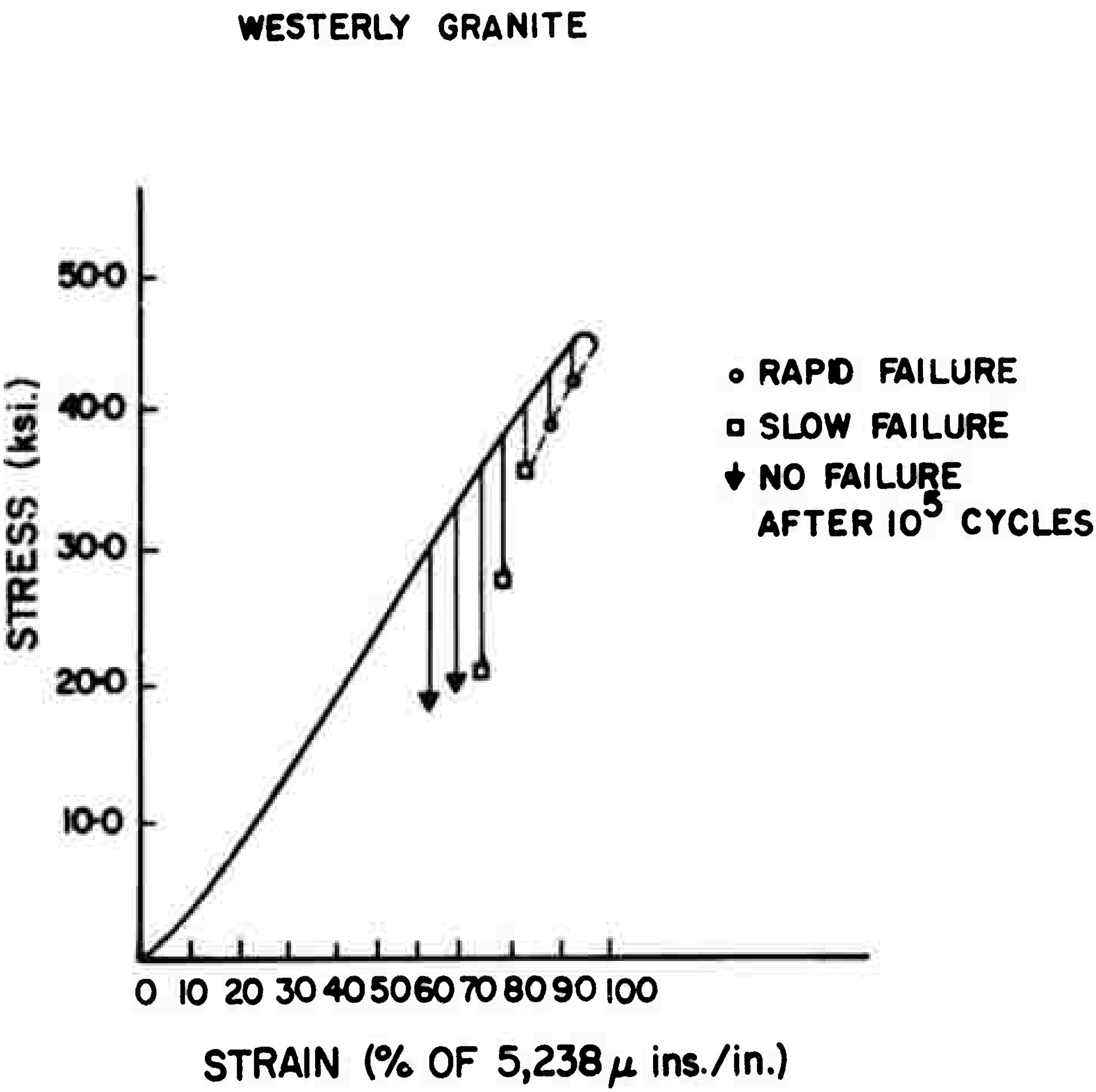

Figure 16. Upper peak stress drop at various strain levels--Westerly Granite.

B - TRIAXIAL COMPRESSION

For the purpose of achieving a closer simulation of real stress conditions underground, a triaxial cell was utilized for the application of confining pressure to the cyclicly loaded specimens. The confining pressure was kept approximately constant during the tests while the vertical load was cycled as in the uniaxial case. The specimens used so far where intact unfailed granite. The fatigue resistance under triaxial conditions was expected to be stronger than that of uniaxially tested samples (5).

The only confining pressure attempted so far has been 1000 psi. Under this condition the "static" compressive strength of Westerly granite was 50,500 psi. The value for which only one cycle was needed to cause fatigue failure was 59,800 psi. Under stress-controlled conditions with constant lower peak stress (kept at 1500 psi, slightly higher than the confining pressure), the shape of the S-N curve (Fig. 17) is strikingly similar to that of the uniaxially loaded granite (Fig. 4). The only difference is that under triaxial conditions the whole S-N curve is lifted upward, i.e., fatigue life is increased for comparable values of maximum cyclic stress. The shape of the S-N curve, as in the uniaxial case can be related to the complete stress-strain curve (3). The value of S = 80% at which fatigue life increases considerably (Fig. 17) appears to coincide with the stress level at which the descending complete stress-strain curve turns from positively sloped to negatively sloped (Fig. 5), and thus requires perhaps more deformation, i.e., more cycles, before fatigue failure.

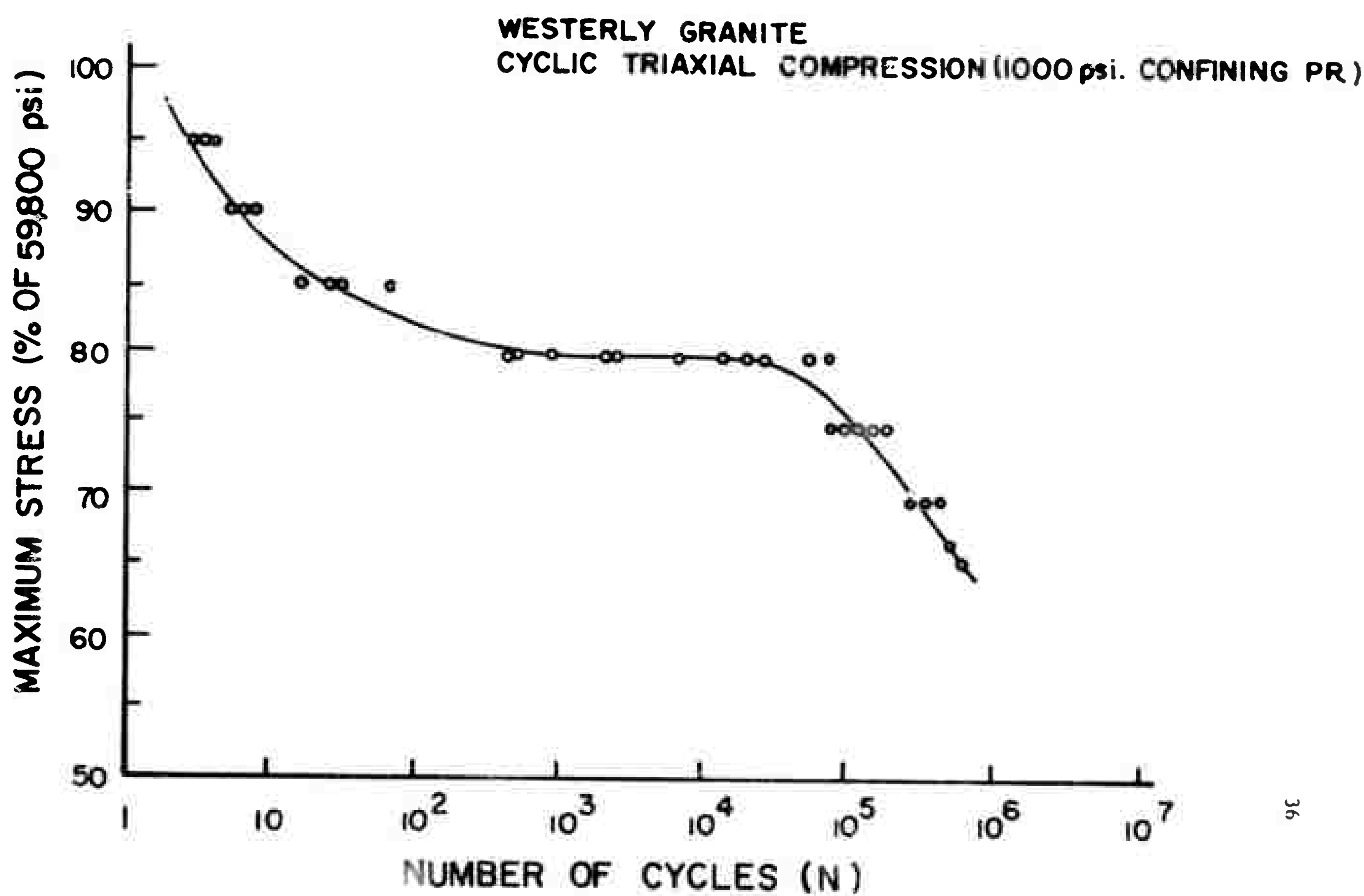

Figure 17. S-N characteristics in triaxial compression--Westerly Granite.

C - UNIAXIAL TENSION

All cyclic tension tests were run in stress-control, at 1 cps. for a maximum of 10^5 cycles. In the previous annual report (1) partial results were presented, based on the experimental work performed in White and Pink Tennessee marble. In this report further results in marble and new work in Indiana limestone and Westerly granite are described.

S-N Characeristics

The S-N characteristics were determined by keeping the lower peak stress constant (about 50 psi tension) throughout the testing program and varying the upper peak stress from test to test. As expected in tension tests of brittle materials, scatter was rather severe. It did not obscure, however, the general trend of rock mechanical reaction to cyclic loading.

In addition to the completion and correction of an already reported curve (1) (Fig. 18), two additional S-N curves were obtained (Figs. 19 and 20). Within the range of maximum cycles per test used (10^5 cycles) straight line approximations appear to best fit the experimental S-N points. The apparent dynamic tensile strengths of the three rocks, at a loading rate equivalent to 1 cps., as determined from the intercept of the S axis with the S-N curve, the fatigue strengths at 10^5 cycles and the static strengths are given in Table 4. Due to the scatter involved, it appears that as a practical application of these results, a value equal to 50% of the static tensile strength could safely be used as a more realistic strength value in the design of hard rock structures subjected to uniaxial tension (static, dynamic, or cyclic).

The Effect of Lower Peak Stress

A number of tests were run on Indiana limestone and Westerly granite to determine the effect of cyclic stress range on fatigue behavior. In both rocks the upper peak load was kept constant during these tests (Fig. 21), while varying the lower peak from test to test. The cyclic frequency was kept at 1 cps. In one series of tests the stress range was zero, i. e., the static fatigue strength was determined. In another series of tests the lower peak was extended into the compression zone. The results are given in Table 5 and Fig. 22.

It is apparent from these results that as the stress amplitude increases, for the same upper peak, the fatigue endurance capacity decreases. In particular, note a difference of two orders of magnitude between the static and the cyclic fatigue life in the limestone, and the considerable weak ening undergone by the granite when it is subjected to a tension-compression cyclic fatigue. The large discrepancy between the static and dynamic fatigue

TABLE 4

TENSILE STRENGTHS AND FATIGUE STRENGTHS

Rock	Tensile Strength at 1 cps (psi)	"Static" Tensile Strength (psi)	Fatigue Strength at 10^5 cycles (psi)	$\frac{\text{Fatigue Strength}}{\text{Static Tensile Strength}} \times \%$ at 10^5 cycles
Pink Tennessee Marble	1625	1400	1100	78
Indiana Limestone	650	670	425	63
Westerly Granite	1600	1385	1050	76

TABLE 5

EFFECT OF LOWER PEAK STRESS ON FATIGUE IN UNIAXIAL TENSION

No. of Specimens	Upper Peak Load (psi)	Lower Peak Load (psi)	Stress Range (psi)	Fatigue Life (cycles)
		Indiana Limestone		
From S-N Curve	600	50	550	14
5	600	400	200	28
5	600	600	0	110[illegible] (secs)
		Westerly Granite		
7	1300	40 (compression)	1340	23
4	1300	50	1250	380
5	1300	420	880	274

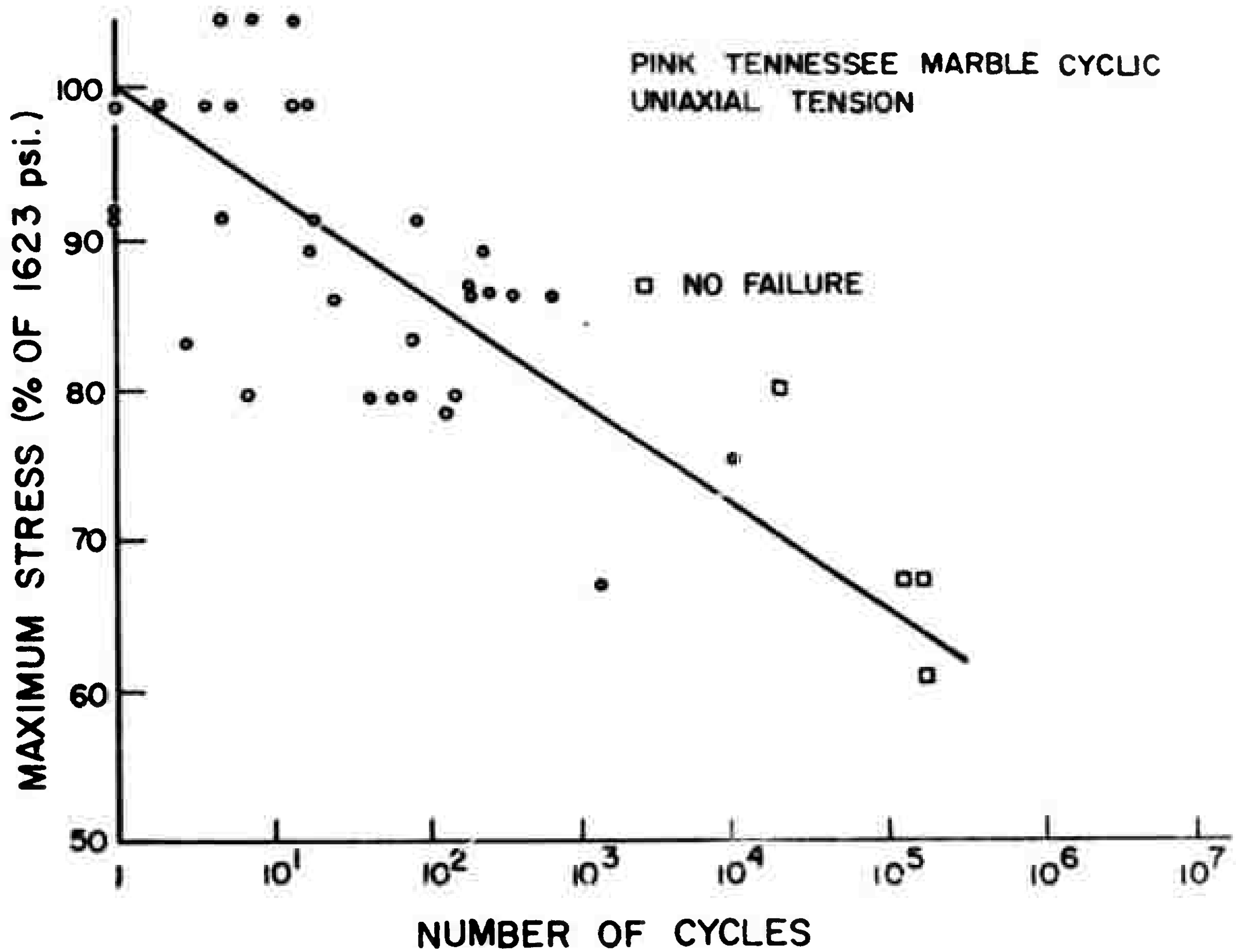

Figure 18. S-N characteristics in uniaxial tension--Pink Tennessee Marble.

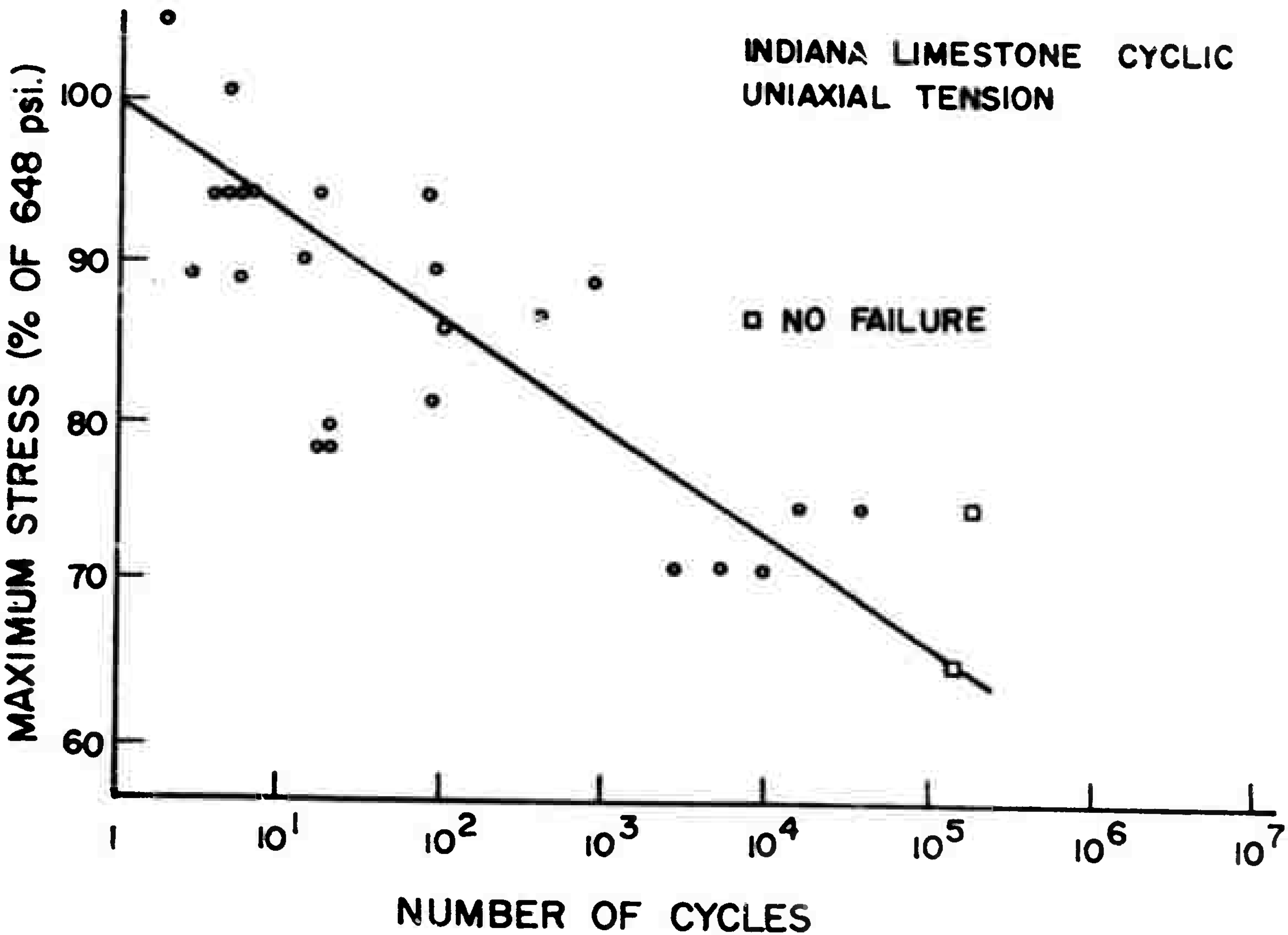

Figure 19. S-N characteristics in uniaxial tension--Indiana Limestone.

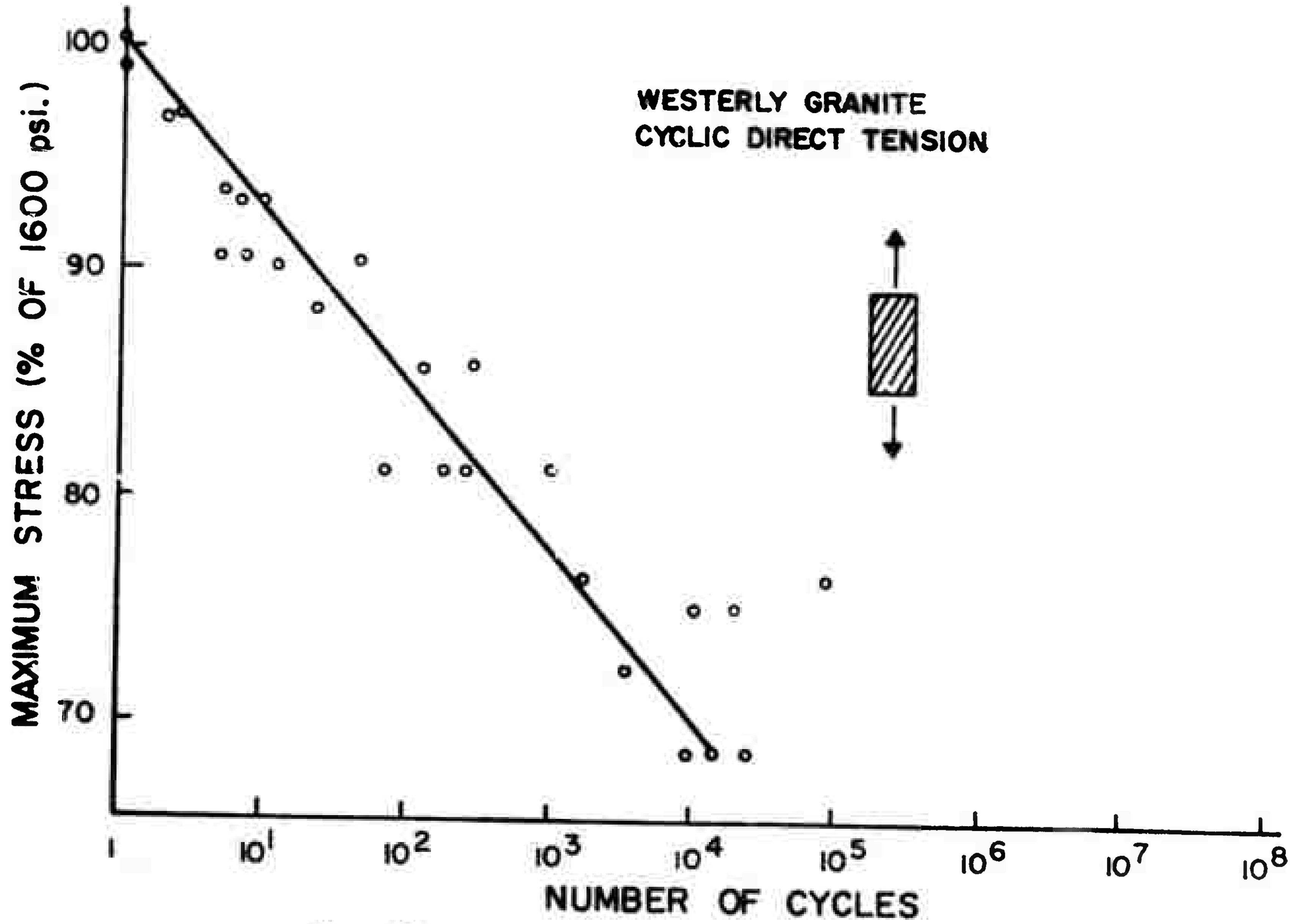

Figure 20. S-N characteristics in uniaxial tension--Westerly Granite.

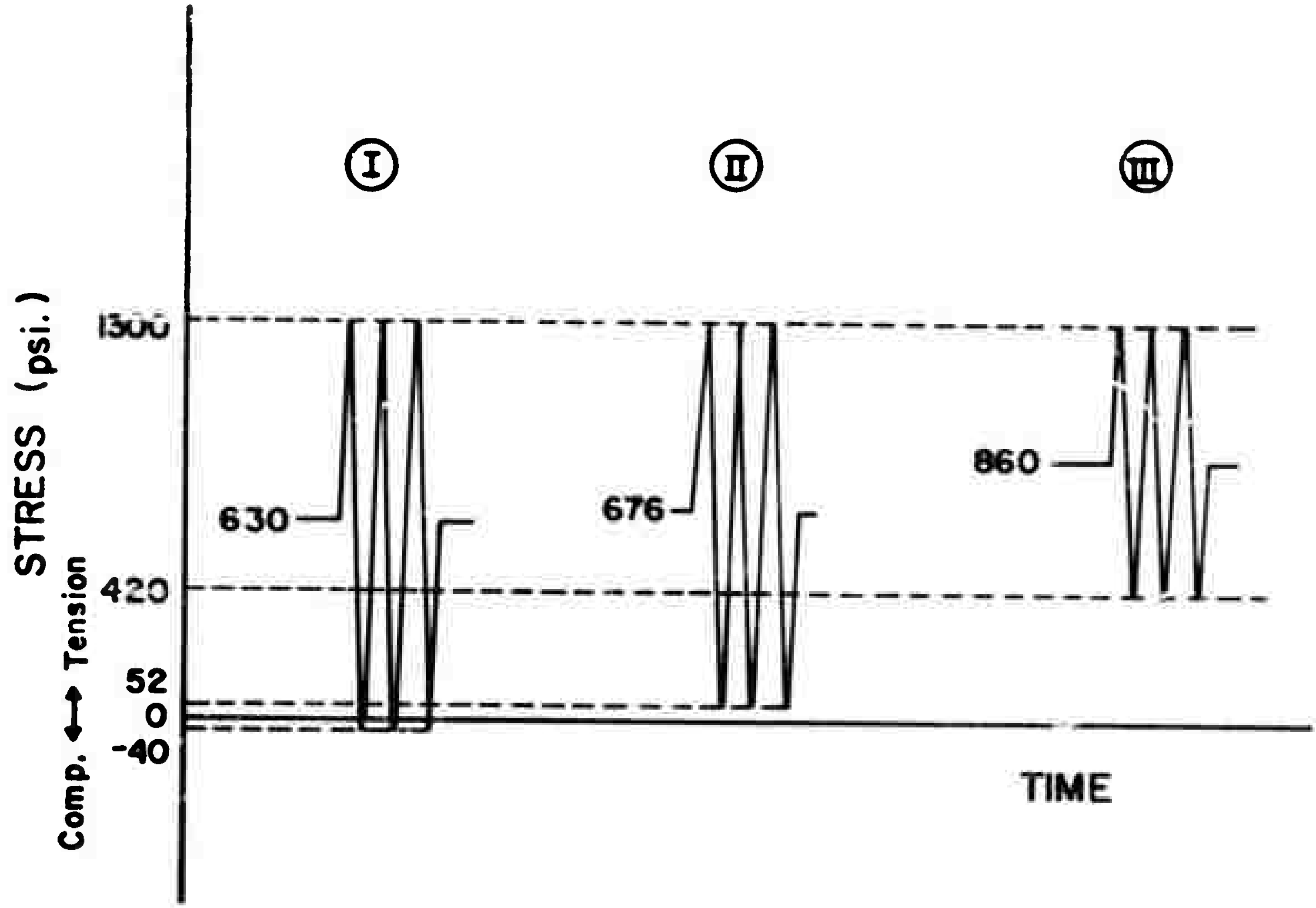

Figure 21. Three stress amplitudes used in cyclic loading of Westerly Granite.

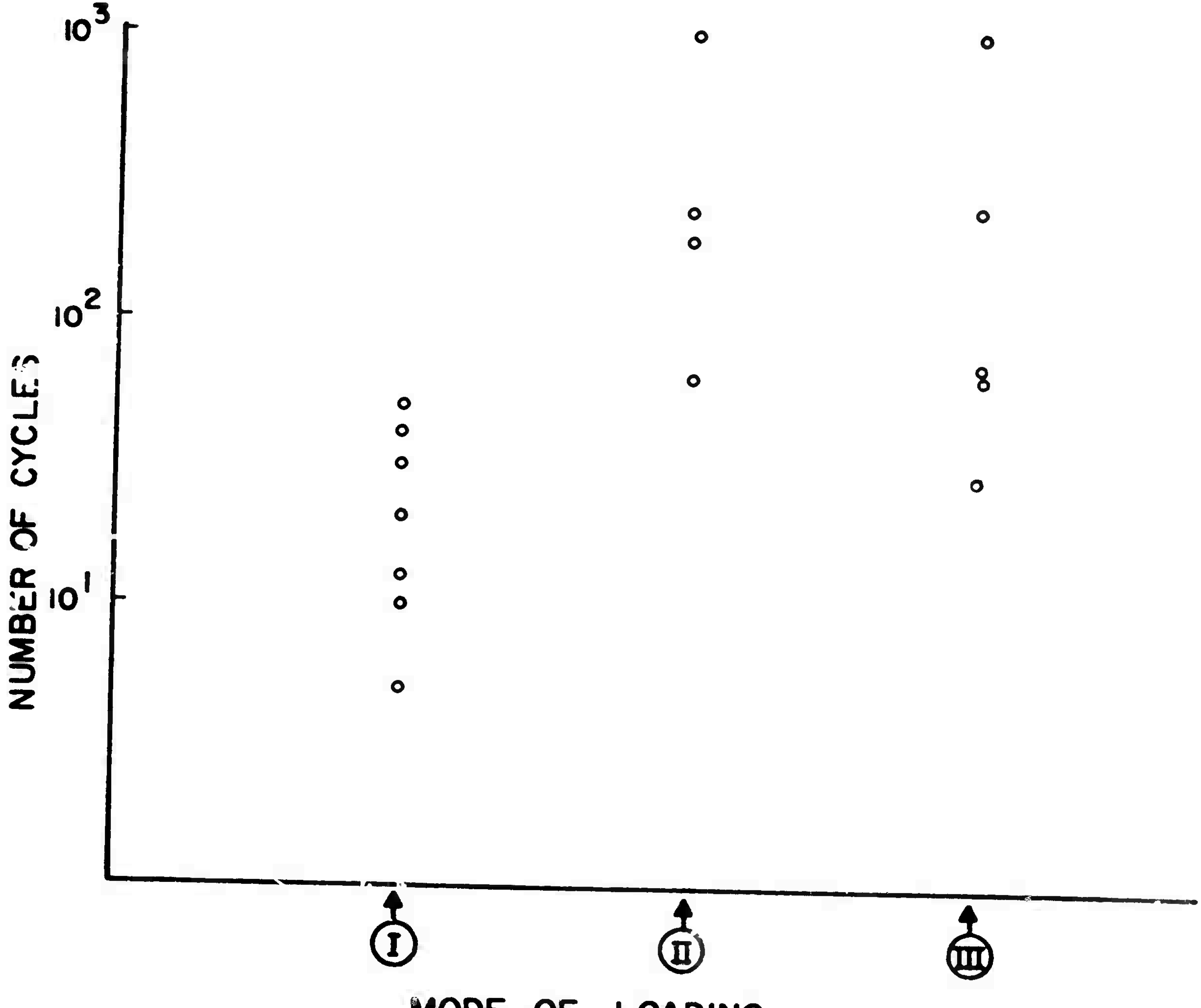

Figure 22. Experimental results of fatigue life for three different stress amplitudes, same upper peak stress--Westerly Granite.

results indicate that the mechanism of cyclic fatigue is basically different from that of creep. The sudden decrease in fatigue life when the lower peak stress goes into the compression zone indicates that tension-compression cyclic stresses may be most damaging and further work in that zone is contemplated.

Stress-Strain Behavior

Stress-strain behavior in cyclic tension is closely analogous to behavior in compression as described in the annual report (1). Probably the most outstanding feature of cyclic loading of rock is the large hysteresis loop in the first cycle. In compression the ascending stress-strain curve of the first cycle is ordinarily concave in the lower half accounting for closing of existing pores and microcracks. In tension the curve appears to be convex with a slope lower than the comparable one in compression. In the second cycle the strain at the lower peak load increases considerably more than at the upper peak and thus an apparent stiffening of the rock takes place. This effect is very pronounced in Indiana limestone (Fig. 23) but hardly noticeable in Pink Tennessee marble (Fig. 24). As cycling continues the upper peak strain increases at a slightly higher rate than the lower peak strain thus softening the rock. By the last cycle the average tangential Young's modulus is approximately equal to that of the first cycle. In Indiana limestone the average value for the Young's modulus at 50% of upper peak load is 2.5 x 10^6 psi. In Pink Tennessee marble it is 7.7 x 10^6 psi. Fatigue failure is preceded in long tests by a few cycles of rapidly increasing strain.

Indiana limestone (Fig. 23) displays considerable hysteresis and non-linearity. Total cyclic creep of the upper peak strain is about 35-50 μin/in. Pink Tennessee (Fig. 24) marble exhibits very little permanent strain in the first cycle, and the stress-strain curve is almost perfectly linear throughout the cycling, with negligible hysteresis and limited cyclic creep (10-15 μin/in).

The longitudinal strain in the cyclic tension tests was recorded by strain gages mounted vertically on the specimens. In both rocks it was noted that unless the fatigue tensile rupture traversed the strain gages, no acceleration was recorded of the permanent strain accumulation immediately preceeding failure. This could imply that this stage of cyclic degradation is very localized in both rocks. Further indications of localized fatigue damage were obtained from observations described in the following sections.

Retested Specimens

As described in the previous report (1) cyclic fatigue in tension culminates in a tensile rupture not unlike that obtained in a static test. The question is whether the fatigue effect is indeed as localized as the rupture implies. In an effort to test the hypothesis of localized fatigue, a number of cyclically failed specimens were reglued together in the plane of rupture and later retested. The reconstruction of the specimens was done

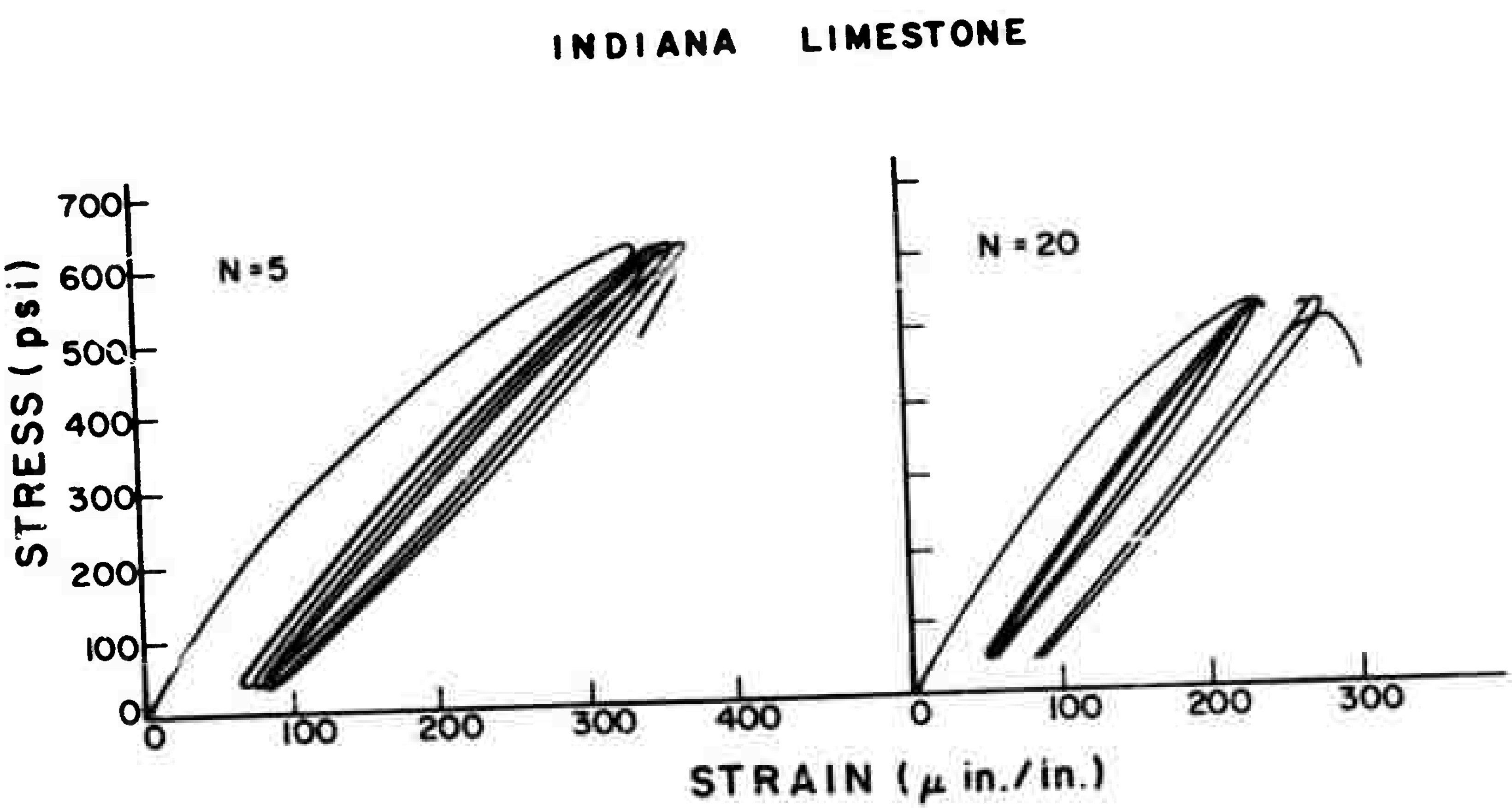

Figure 23. Typical stress-strain curves in stress controlled cyclic uniaxial tension--Indiana limestone.

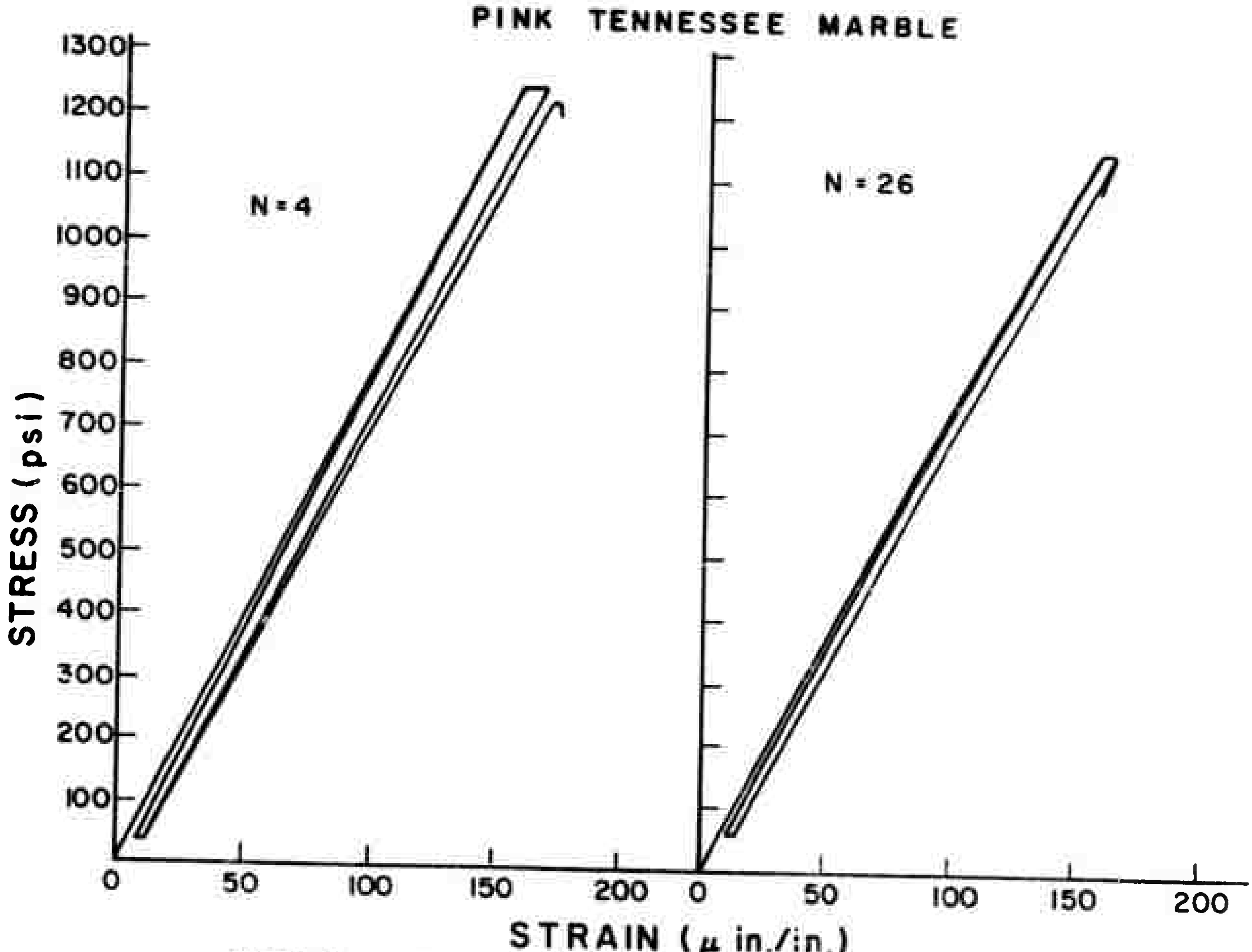

Figure 24. Typical stress-strain curves in stress controlled cyclic uniaxial tension--Pink Tennessee Marble.

with the same epoxy cement used to join rock to end caps. All excess epoxy was squeezed out and utmost care was taken to ensure that the alignment of the original specimen was not disturbed by the reglueing.

The results are summarized in Table 6. Specimens initially failed after less than 10^3 cycles showed reduced fatigue resistance when retested. Those initially surviving 10^4 cycles or more showed improved fatigue resistance. In the two very short tests, the second failure surface was 1/16 inch away from the first, suggesting that there was some secondary damage adjacent to the original failure plane. Such secondary damage in the form of a few minor additional cracks near the main one was commonly observed in both monotonic and fatigue failed specimens. In the other specimens the second failure surface was at least 1/4 inch from the original and usually farther away. This seems to suggest that less secondary failure occurred in these specimens. If the specimens had been completely homogeneous and if fatigue damage had been uniformly distributed over the specimens, all of them would have failed during the first cycles of the retest. That they did not, and that some were actually stronger the second time suggests two hypotheses: (a) tensile fatigue failure in rock is quite localized, (b) fatigue damage becomes increasingly localized at smaller stresses.

Microscopic Examination

Most of the microscopic work was conducted on polished vertical sections of untested and tested (failed) specimens. In addition, in some Pink Tennessee marble specimens portions of the outside surface was polished prior to testing, photographed, subsequently fatigued and re-examined for before and after differences.

Generally, in both Indiana limestone and Tennessee marble no appreciable fabric changes due to fatigue were observed. In the pre-photographed specimens, however, it was noticed that some final failure surfaces followed the planes of pre-existing cracks. Frequently the final rupture surface cut across grains following cleavage planes. Preliminary results of the microscopic study support the hypothesis of localized fatigue damage and failure. A full account of the work will be included in the annual report.

TABLE 6

INDIANA LIMESTONE RETESTED SPECIMENS

Specimen Number	Upper Peak Stress (% of tensile strength)	Fatigue Life Initial Test	Fatigue Life Retest	Monotonic Strength if unfailed after stated cycles in retest (% of tensile strength)
20	94	5	1	—
21	94	4	1	—
40	89	90	40	—
35	88	845	10	—
47	74	35,700	228,000+	91.4
29	71	9,260	198,410+	101.0

CONCLUSIONS AND PRACTICAL APPLICATIONS

The experimental work carried out in the first six months of the present contract confirmed for additional hard rock types some of the conclusions presented in the first annual report, and contributed new and important findings of its own.

1. Berea sandstone and Westerly granite, like the previously tested Tennessee marble and Indiana limestone were weakened considerably by cyclic uniaxial compression. Indiana limestone and Westerly granite like the previously tested Tennessee marble showed considerable weakening when subjected to cyclic uniaxial tension. In addition Westerly granite lost strength under cyclic compression even when assisted by a confining pressure of 1,000 psi. All these results give more strength to the assertion that hard rock is fatigue prone. Design of structures in rock cannot ignore the effects of repetitive loading. The fatigue strengths of each rock as determined by the reported tests could be used as the effective strengths of intact rocks. Since not every rock in the field can be extensively tested, it is appropriate to suggest an empirical formula based on the results obtained thus far. It is therefore recommended that a value of 50% of the appropriate static strength (compressive or tensile) be used as the effective strength that can withstand static, dynamic and cyclic loading.

2. Prefailed Westerly granite, like the previously tested prefailed Georgia and Tennessee marbles, exhibited substantial fatigue endurance, although the fatigue life at each stress level was much reduced when compared with unprefailed rock. This work does not provide quantitative results but helps recognize the importance of considering the strength capacity of failed rock as encountered in underground pillars and walls.

3. Additional experimental evidence was collected in support of an inter-relationship between rock fatigue and the respective complete stress-strain curve. Particularly in granite, the amount of permanent deformation exhibited by the upper peak strain in stress-controlled tests, the shape of the S-N curve, the amount of peak stress relaxation and the type of fatigue failure in strain controlled tests, all allude to a Class II rock type and match the characteristics of the complete stress-strain curve. The practical application of this conclusion cannot be overlooked. Determining the complete stress-strain curve for a rock under specific conditions of loading rate and triaxial stress configuration is much easier and less time consuming than preparing an S-N curve. Monitoring the amount of accumulated permanent deformation at a particular stress level (whether in a laboratory specimen or an underground structure) and comparing it

with the allowable magnitude from the complete stress-strain curve, one could evaluate the stability condition and estimate the amount of cyclic loading that the rock can still withstand. The shape of the complete stress-strain curve could indicate the ranges of maximum stress for which the rock is more susceptible to fatigue effects. These are the regions of minimum allowable permanent strain, usually caused by those portions of the descending stress-strain curve having positive slopes.

4. An additional indication that the maximum allowable permanent strain at a particular upper peak stress actually controls the fatigue endurance of rock was found in tests where the upper peak load was varied in two or three steps during cycling. The total permanent strain for the last maximum stress level used was independent of the loading path, being apparently controlled only by the shape of the complete stress-strain curve.

5. Experiments in uniaxial tension with different cyclic amplitudes for the same upper peak stress shosed that the cyclic stress range considerably affects fatigue life. In particular, the experiments implied that tension-compression cyclic loading could be the most damaging type.

6. Previous investigation of the compression fatigue mechanism showed that the process of cumulative damage was spread through the entire specimen. In uniaxial tension fatigue, however, fabric changes due to cyclic loading appear to be very localized, i.e., a few of the more crucial existing microcracks slowly enlarge until one gains on the others, propagates and splits the specimen. Other than the very close vicinity of the rupture plane no changes were observed in the internal structure of the rock. The implication here is that unlike compression fatigue, inpending tensile fatigue failure may give little warning in terms of deformation away from the critical flaw.

FUTURE WORK

1. Complete the uniaxial compression and tension cyclic testing.

2. Establish the fatigue effect on rock under different triaxial conditions.

3. Study fatigue characteristics of rock under tension-compression cyclic loading.

4. Determine the mechanical response of non-intact rock to repetitive loading.

5. Carry out fabric studies to complete the investigation of internal fatigue mechanisms.

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